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EXPERIMENTAL PERFORMANCE OF TWO SEGMENTED WALL MAGNETOHYDRODYNAMIC ELECTRIC POWER GENERATORS USING SOLID-FUELED COMBUSTORS

M. A. Nelius, R. J. LeBoeuf, and J. D. McNeese

ARO, Inc.

July 1968

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FOREWORD

The test program reported herein was conducted at the request of the Air Force Aero-Propulsion Laboratory (AFAPL), Air Force Systems Command (AFSC), Wright-Patterson Air Force Base, Ohio under Contract AF 33(615)-2691 for the University of Tennessee Space Institute (UTSI) under Program Element 62405214, Project 5350, Task 535004.

The results of the test were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract F40600-69-C-0001. The test was conducted from July 12 to September 8, 1967, in Propulsion Research Area (R-2C-4) of the Rocket Test Facility (RTF) under ARO Project No. RW0637, and the manuscript was submitted for publication on January 31, 1968.

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This technical report has been reviewed and is approved.

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ABSTRACT

A test program was conducted for the University of Tennessee Space Institute on a vertically segmented wall (Hall) and a diagonally segmented wall (45-deg-slant) magnetohydrodynamic generator. The internal width of the 48-in. -long generator channel was 2 in. ; the height diverged from 4 in. at the inlet to 6 in. at the exit. The plasma was provided by a solid-fueled combustor with a nozzle designed for an exhaust gas exit Mach number of 3.75. Thirteen firings were made with the 45-deg-slant channel for power generation. Six firings were made with the Hall channel; three of these were for power generation, and three were made for exhaust gas conductivity measurement. Operating conditions for the power generation firings were: nominal combustor chamber pressure, 325 psia; magnetic field, 20,000 gauss; and load bank resistance from 0 to ∞ ohms. For the exhaust gas conductivity measurements, voltage was supplied to the channel at levels of 360, 440, and 200 v dc. Tabulations of combustor performance and of the electrical data from the two generator configurations are presented.

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SECTION I INTRODUCTION

A magnetohydrodynamic (MHD) electric power generator is classed as a direct energy conversion device. Ionized gas flowing at high velocity through a channel is acted on by a transverse magnetic field to produce an electromotive force perpendicular to the velocity vector and to the magnetic field. The same physical principles are involved in an MHD generator as in a conventional generator except that conducting gases replace the metallic conductors of the rotor.

The University of Tennessee Space Institute (UTSI) is currently engaged in a research investigation of parameters governing the performance of open-cycle MHD devices. The program is designed to provide correlation between theoretical and experimental performance of several types of MHD generators in order to establish basic generator design criteria. The scope of the experimental effort includes a parametric study to optimize the performance of 45-, 60-, and 75-deg-slanted, Hall and Faraday generator channels operating at various gas dynamic conditions, electrical loads, and magnetic fields. The walls of each of the channels are segmented to reduce the effect of the Hall field.

Earlier test phases (Refs. 1 through 4) utilized a $\text{GO}_2/\text{RP-1}$ combustor with Alcohol/KOH seed to provide ionized gas. This report presents the data obtained from a vertically segmented wall (Hall) and a diagonally segmented wall (45-deg-slant) MHD generator channel using a solid-fueled plasma generator. A description of the combustor, channels, magnet, and associated systems is given, and the methods used to obtain the required measurements are presented.

The test program reported herein was conducted in Propulsion Research Area (R-2C-4) of the Rocket Test Facility (RTF). The RTF personnel were responsible for design and fabrication of the combustor support stand, the combustor ignition system, the exhaust gas cooling systems, and associated instrumentation systems. The combustors, channels, magnet, diffuser, load banks, and electrical meters were supplied by UTSI.

SECTION II APPARATUS

2.1 TEST ARTICLE

The test article consisted of a combustor, an MHD generator channel and diffuser, and a magnet. These components and the supporting systems

(load bank, magnet power supplies, spray chamber, and shunt panel) are described in detail in the sections to follow.

2.1.1 MHD Generator Channel and Diffuser

Two MHD generator channels were employed: a diagonally segmented wall (45-deg-slant) channel (Fig. 1, Appendix I) and a vertically segmented wall (Hall) channel (Fig. 2).

The copper channels were nominally 48 in. long with outside dimensions of 3.75 in. wide by 8 in. high. The inside dimensions were 2 in. wide by 4 in. high at the inlet with the side walls parallel and the top and bottom walls diverging to 6 in. high at the exit. The 36-in. active length of the channels (conforming to the 36- by 6-in. magnetic field cross section) was assembled from several individually insulated wall segments, each segment acting as an electrode. The remaining 12 in. of the channel lengths (nominally 6 in. at each end) was made of copper blocks (transition elements) insulated from each other to reduce eddy currents. Each element and block was attached to the adjacent elements or blocks by ceramic-insulated stainless steel screws.

The 45-deg-slant wall channel segments (Fig. 3) were made of 0.417-in. -thick copper slabs electrically insulated from each other by 0.018-in. -thick mica paper. The segments were inclined forward at 45 deg to the channel axis to form a laminate array 40 in. long, of which 2 in. at each end was part of the inactive portions of the channel. The remaining 4 in. at each end was composed of transition elements. Each of the 50 full segments was split at the middle to form top and bottom elements, also insulated from each other by 0.018-in. -thick mica paper. These elements and the 16 partial end segments comprised the electrodes.

The Hall channel segments (Fig. 4) were 0.582 in. thick and arranged perpendicular to the axis of the channel. The segments of the Hall channel were split at the middle and insulated similar to the 45-deg channel. Sixty segments, with insulation, comprised the 36-in. active length of the Hall channel; the remaining 6 in. at each end was comprised of transition elements.

The diffuser was made from 1/2-in. -thick stainless steel plates, with a 2- by 6-in. internal cross-sectional area and a 24 1/2-in. length. The front flange of the diffuser was bolted to the aft flange of the channel. The aft flange of the diffuser was adapted to the forward bulkhead of the spray chamber with a rubber slip joint seal and extended 8 in. into the spray chamber.

2.1.2 Magnet

The magnetic field was provided by a 20,000-gauss electromagnet (Fig. 5) and was directed normal to the vertical plane containing the channel axis. The distance between the magnet pole faces was 3.96 in.; each face was 6 in. high by 36 in. long.

The magnet was of 'C' frame construction with eight strip-wound coils, six coils having 48 turns each and two coils having 55 turns each (Fig. 5c). Each coil was designed to conduct 600 amp for a total of 238,800-amp turns. The magnetic field strength is presented in Fig. 6 as a function of current. Water cooling coils were installed adjacent to, but insulated from, the electrical coils. Cooling water was supplied at a nominal flow rate of 55 gal/min at a nominal inlet pressure of 70 psig. In the event of an accidental power failure, the energy stored in the magnetic field would be dissipated through a 0.040-in. spark gap located in the electrical terminal box.

Current to the magnet was supplied by fifteen, 400-amp, 40-v dc power supplies (Fig. 7) connected in five parallel arrays of three each in series.

2.1.3 Load Bank

The electrical power produced by the MHD generator was dissipated as heat through four air-cooled resistive load banks, each bank containing 252 resistor elements (Fig. 8). Each load bank was capable of dissipating 100 kw. The individual resistors were strapped to form the desired parallel and series arrangements for impedance matching to the generator electrical output.

2.1.4 Combustor

Ionized gas to the MHD generators was provided by solid-fueled combustors (Fig. 9) produced by Hercules, Inc. The combustors utilized type VJP solid-fuel/oxidizer grains (Fig. 10) having a cylindrical bore, center-perforate design with uninhibited end burning. The reactants were cast in an insulating beaker of phenolic. The net weight of reactants in each grain was nominally 8 lb_m.

The combustion chamber was fabricated from 5-in. -diam schedule 40 stainless steel pipe. The transition from a circular chamber to a rectangular nozzle exit cross section was accomplished in the diverging supersonic nozzle section downstream of the nozzle throat. A photograph showing the graphite transition section is presented in Fig. 11. The transition section flow area diverges from 0.50 in.² at the throat to 8 in.² at the exit (2 by 4 in.), providing a nominal exit Mach number of 3.75.

The grains were ignited by two US Flare 207 D1 squibs immersed in a bag containing powdered BKNO_3 which was surrounded by BKNO_3 and magnesium Teflon® pellets. The igniter assembly was contained in the igniter head by a 5-mil polyurethane disk (Fig. 9).

2.2 INSTALLATION

The combustor, magnet, channel, and diffuser were installed in Propulsion Research Area (R-2C-4). A photograph and a schematic of the installation are shown in Fig. 12. The magnet was installed on the magnet support stand, and the channel was placed on a support stand between the magnet pole faces. The forward flange of the channel was aligned with, and bolted to, the combustor nozzle flange. The channel diffuser extended through the forward bulkhead of a spray chamber. A 12-in. exhaust duct was bolted to the downstream end of the spray chamber to direct the cooled exhaust gases into the facility exhaust system.

The spray chamber (Fig. 13) was a 36-in.-diam, 10-ft-long cylinder made of 1/4-in. mild steel. An air spray ring was located just forward of the diffuser exit plane (Fig. 12b) to provide a nonconducting shroud around the ionized exhaust gases, thereby preventing electrical conduction to the spray chamber walls until the exhaust gases are cooled below the ionization temperature. Four water spray rings were used to cool the exhaust gases before discharge into the 12-in. exhaust duct. The spray chamber was insulated against 2000-v potential from ground. The supply lines and drain line were made of cotton braid rubber hose. The resistance to ground was about 1000 ohms with the 6-in. drain line full of cooling water.

A shunt panel (Fig. 14) was used as an electrical interface between the channel and the load bank. The panel contained low resistance (0.0005-ohm) shunts, across which current between channel elements and between the channel and load bank was measured. Voltage taps and fuses to protect the meter circuits and load bank circuits were also provided in the shunt panel.

Typical electrical circuits used for the 45-deg-slant channel are shown in Fig. 15. Circuits for the Hall channel are shown in Figs. 16 and 17. The electrical measurements made during power generation firings were: (1) voltage across the load resistors, (2) current from channel electrodes to the load bank, and (3) channel element top-to-bottom current. Electrical measurements made during exhaust gas conductivity runs were: (1) channel axial voltage, (2) power supply voltage, and (3) plasma current. For the channel elements not shown in Figs. 15 through 17, the even-numbered elements through number 50 were shorted top-to-bottom and the odd-numbered elements through number 49 were shorted top-to-bottom.

through ammeter shunts. For both channels, elements 51 were shorted directly top-to-bottom and elements 52 were shorted top-to-bottom through ammeter shunts. Current from the four segments at the upstream end and the four segments at the downstream end of each channel to the load bank was carried by 3/0 cable, and current from element top-to-bottom and from element to load bank for all other segments was carried by No. 2 AWG 600-v cable.

2.3 INSTRUMENTATION

Instrumentation was divided into two distinct groups: support equipment instrumentation and channel and magnet instrumentation. Instrument ranges, recording methods, and an estimate of measurement uncertainty for all measured parameters are presented in Table I (Appendix II).

2.3.1 Support Equipment Instrumentation

Instrumentation was provided to measure combustor chamber pressure, nozzle exit static pressure, and spray chamber pressure.

The output signal of each measuring device was recorded on independent instrumentation channels. The combustor chamber pressure data were recorded as follows: Each output signal was transmitted to a millivolt-to-frequency converter. A magnetic tape system, recording in frequency form, stored the signal from the converter for reduction at a later time by an electronic digital computer. The computer provided a tabulation of average absolute values for each 0.1-sec time increment. A photographically recording, galvanometer-type oscillograph recording at paper speeds ranging from 6 to 60 in./sec provided an independent backup of combustor chamber pressure. The nozzle exit-static pressure and spray-chamber pressure data were recorded on magnetic tape from a multi-input, high-speed, analog-to-digital converter at a scan rate for each channel of 75 times/sec. Playback of these tapes on a digital computer provided a tabulation of average absolute values for each 0.1-sec time increment.

2.3.2 Channel and Magnet Instrumentation

Generator voltages and currents and magnet voltage and current were displayed on an array of meters located on a rack-mounted meter panel (Fig. 18) and insulated from 2000-v potential to ground. The data from these meters were recorded photographically by a 70-mm camera that was timer actuated to provide photographs at approximately 1-sec intervals during a power generation firing. These photographs were time correlated

with engine burn time by "camera pulses" recorded on the oscillograph. Selected generator voltages recorded on the oscillograph provided a continuous recording of generator performance during firing.

SECTION III PROCEDURE

After the receipt of the component parts of the combustors and the MHD generator channels at AEDC, the fuel/oxidizer grains were weighed and radiographically inspected for cracks, voids, or separation and found to meet the acceptance criteria provided by the manufacturer. During storage in an area temperature conditioned at $75 \pm 5^\circ\text{F}$, the combustors were checked to ensure correct fit of mating hardware, and the nozzle throat and exit diameter measurements were obtained. The electrical resistance between the individual segments of the MHD generator channels was measured to verify that no electrical shorts existed.

The channel was installed and aligned between the magnet pole faces, and the electrical leads were connected to the shunt panel. The combustor transition section housing and the exhaust diffuser were connected to the channel attachment flanges, and the entire assembly was checked to ensure that the generator was electrically isolated from ground.

After the combustor nozzle, case, grain, and igniter had been assembled, pre-fire calibrations were completed, and the channel exhaust pressure was reduced to 3.0 psia. The firing circuit resistance was set to provide the required 4-amp igniter current, and the magnet current was adjusted to provide the desired magnetic field. The entire instrumentation measuring-recording complex was activated, and the combustor was fired.

The channel exhaust pressure was then returned to ambient conditions, post-fire instrumentation calibrations were made, and the channel and combustor were inspected. The combustor was disassembled, the nozzle throat and exit diameters were measured, and post-fire photographs were obtained.

SECTION IV RESULTS AND DISCUSSION

Nineteen solid-fueled combustors were fired to determine the performance of two MHD generator channel configurations and to evaluate

the electrical conductivity of the products of combustion. The plasma was supplied to the channel inlet at a Mach number of 3.75 (based on compressible flow tables for $A/A^* = 13.0$, $\gamma = 1.28$) and a nominal total pressure of 325 psia. The run durations were nominally 7 sec.

Power generation testing was accomplished at a magnet field strength of 20,000 gauss with a diagonally segmented wall (45-deg-slant) channel (13 firings) and a vertically segmented wall (Hall) channel (three firings). The channel external resistance load was varied from 0 (short circuit) to ∞ (open circuit) ohms during 45-deg-slant channel testing but was held constant at 6 ohms for the three Hall channel power generation firings. A voltage was applied between the upstream and downstream Hall channel electrodes with an external power supply during three firings (with no magnetic field) to determine the electrical conductivity of the plasma.

The combustor performance data are summarized in Table IIa. The test variables (channel configuration, electrical hook-up configuration, load bank resistance, and magnet field polarity) are shown in Table IIb. The measured values of load bank resistances (corresponding to the resistor designations shown in Fig. 15) are shown in Table III. Detailed electrical measurements are presented in Tables IV, V, and VI for the thirteen 45-deg-slant channel power generation firings, the three Hall channel power generation firings, and the three exhaust gas conductivity measurement firings, respectively.

4.1 COMBUSTOR OPERATING CHARACTERISTICS

The variation in chamber pressure, nozzle exit side wall static pressure, and spray chamber pressure during a typical firing is shown in Fig. 19. Also shown is the chamber pressure variation during firings having the highest and lowest values of average chamber pressure. Although the 19 combustor assemblies used during this program were macroscopically identical, some variation in the burning characteristics existed between individual motors. Action time, defined as the time interval between 10 percent of maximum chamber pressure during ignition and 10 percent of maximum chamber pressure during tailoff, ranged from 6.05 to 7.42 sec (Table IIa). Nozzle throat erosion resulted in throat area increases of from 32 to 50 percent of the pre-fire area. A layer of combustion products, determined from chemical analysis to be primarily aluminum oxide, was deposited on the walls of the combustor nozzle (Fig. 20) and channel during each firing. The aluminum oxide, which is a relatively good electrical insulator, was removed from the nozzle and channel walls after each motor firing. No significant variation in the nozzle exit pre- and post-fire areas was observed after removal of the exhaust products.

4.2 GENERATOR ELECTRICAL PERFORMANCE

Primary electrical data were obtained from the meter indications of channel currents and voltages which were photographically recorded at 1-sec intervals during the firings. The total channel axial voltage was continuously displayed on an oscillograph recorder during the firings to provide an indication of the channel transient electrical operating characteristics. The variation of total channel voltage with motor chamber pressure during the 45-deg-slant wall channel firings and the Hall channel power generation firings is shown in Figs. 21 and 22, respectively. The electrical data presented in Tables IV and V were obtained from the meter panel photograph which indicated the highest value of total channel voltage during each firing.

The power generated during the 45-deg-slant wall channel power generation firings is shown in Fig. 23 as a function of center resistance load. The variation in generated power between firings conducted at nominally equivalent loads is attributed to variations either in the chamber pressure level between the firings or to voltage instability. Arcing occurred between the channel and ground during two of the firings conducted at a resistance load of 7 ohms.

The three Hall channel power generation firings were accomplished at identical loading conditions ($R_c = 5.98$ ohms), with the only test variable being the magnet field polarity. During the firing accomplished at "normal" magnet field polarity, the generated power was 27.2 kw, and the channel top electrodes were electrically positive with respect to the bottom electrodes. During the two firings accomplished with the magnet field reversed, the generated power was 16.4 kw, and, as expected, the channel bottom electrodes were electrically positive with respect to the top electrodes.

The power generated during the Hall channel firings was approximately 80 percent less than that generated during the 45-deg-slant channel firings at comparable test conditions.

The Hall channel axial voltage distribution observed during the conductivity measurement firings is presented in Fig. 24. Voltage was applied to the channel between electrodes 3, 4, 5, 6, 7, and 54, 55, 56, 57, 58. The variation in applied voltage, the current conducted through the plasma, and motor chamber pressure during a typical conductivity measurement firing is shown in Fig. 25.

The gas conductivity was determined by dividing the axial distance between points of voltage application by the product of the average flow

passage area and the plasma electrical resistance $\left(\frac{E}{I}\right)$. The average gas conductivity between electrodes 10 and 50 was determined to be 40, 49, and 45 mhos/meter for the firings conducted at applied voltages of 360, 440, and 200, respectively.

SECTION V SUMMARY OF RESULTS

Nineteen solid-fueled plasma generator firings were performed using Hercules, Inc., type VJP propellant. The cylindrical bore, center-perforated grains had uninhibited end burning and weighed approximately 8 lb. Thirteen firings were for power generation through the 45-deg-slant wall channel, three firings were for power generation through the Hall channel, and three firings were for plasma conductivity measurement through the Hall channel. The test results are summarized as follows:

1. The maximum power generated was 160 kw, using the 45-deg-slant wall channel with a load bank center resistance of 7 ohms.
2. Power generated using the Hall channel was 27.2 kw with a load bank resistance of 6 ohms and normal magnetic field polarity and 16.4 kw with a load bank resistance of 6 ohms and reversed magnetic field polarity.
3. Plasma conductivity was 40, 49, and 45 mhos/meter at applied voltages of 360, 440, and 200, respectively.

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APPENDIXES

I. ILLUSTRATIONS

II. TABLES

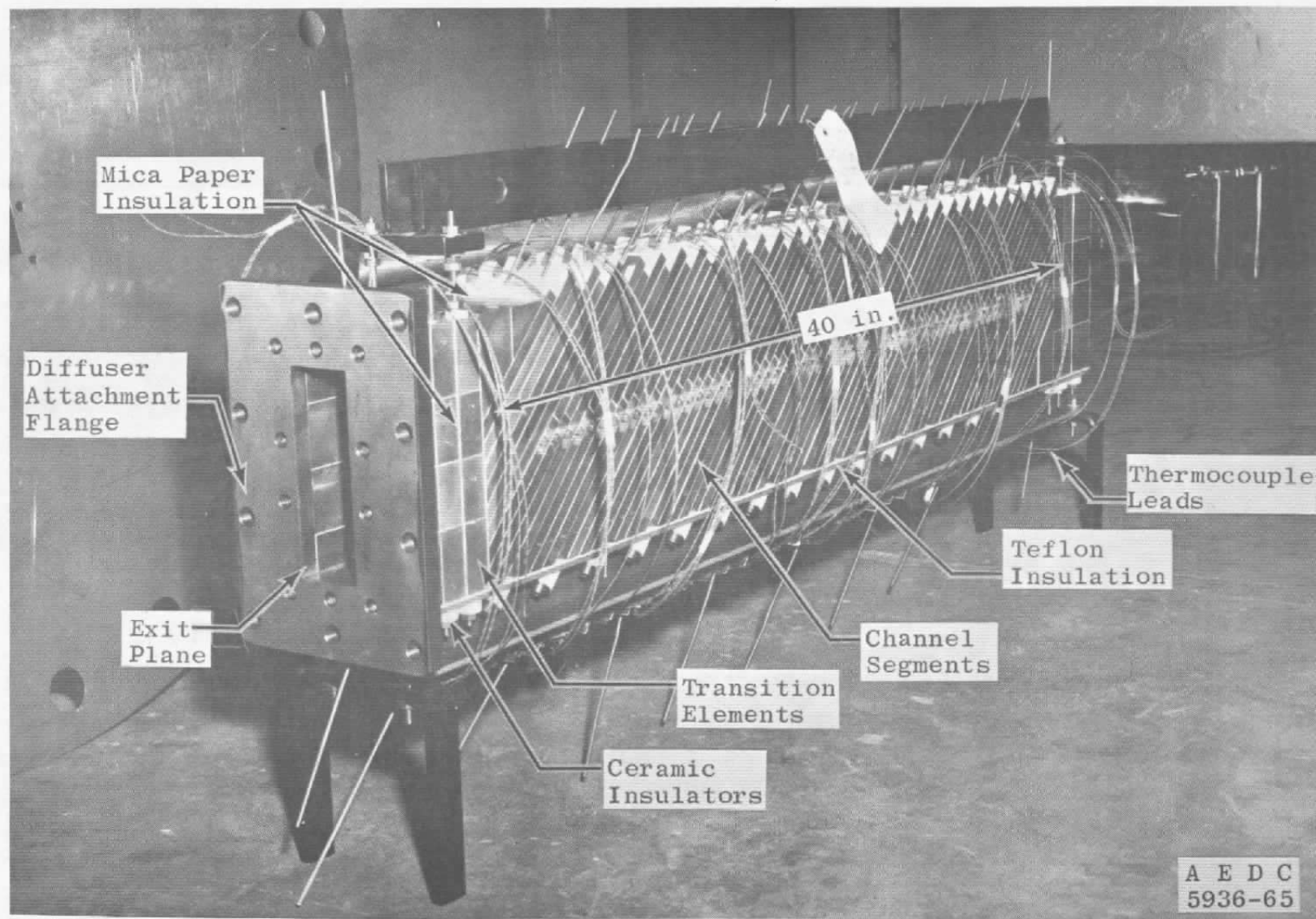


Fig. 1 Photograph of 45-deg-Slant Segmented Wall Channel

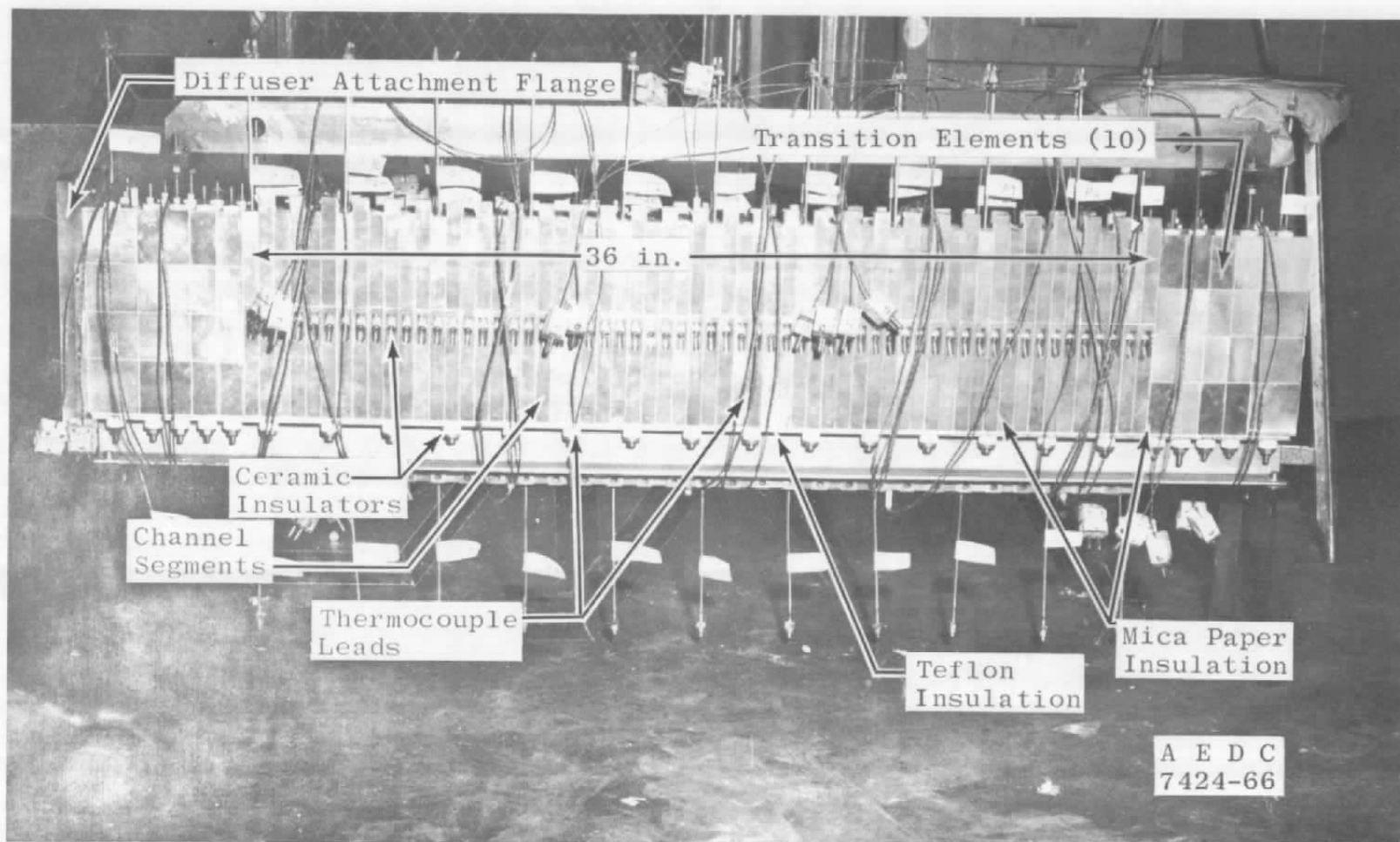


Fig. 2 Photograph of Vertically Segmented Wall (Hall) Channel

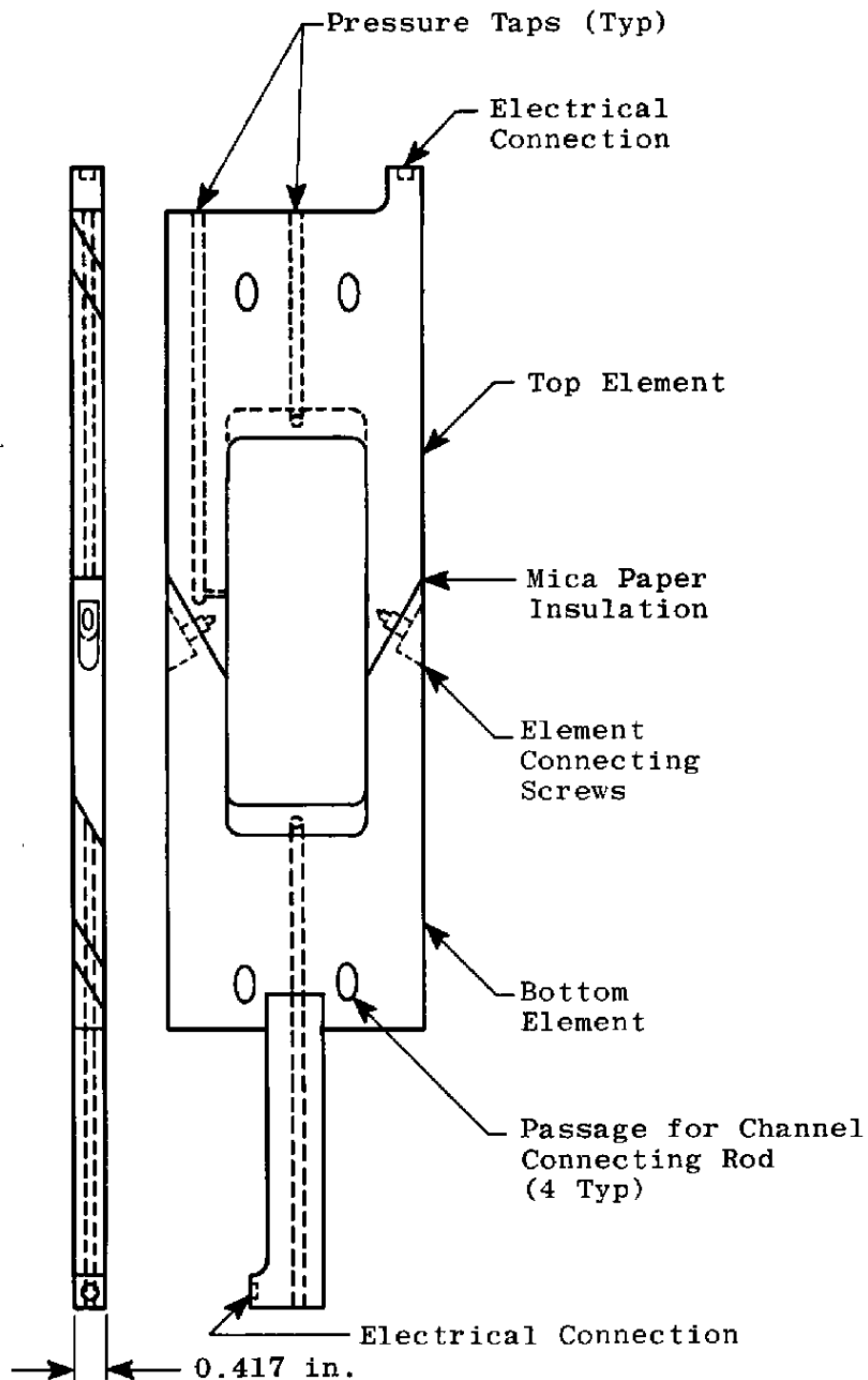


Fig. 3 Schematic of Typical 45-deg-Slant Wall Channel Segment

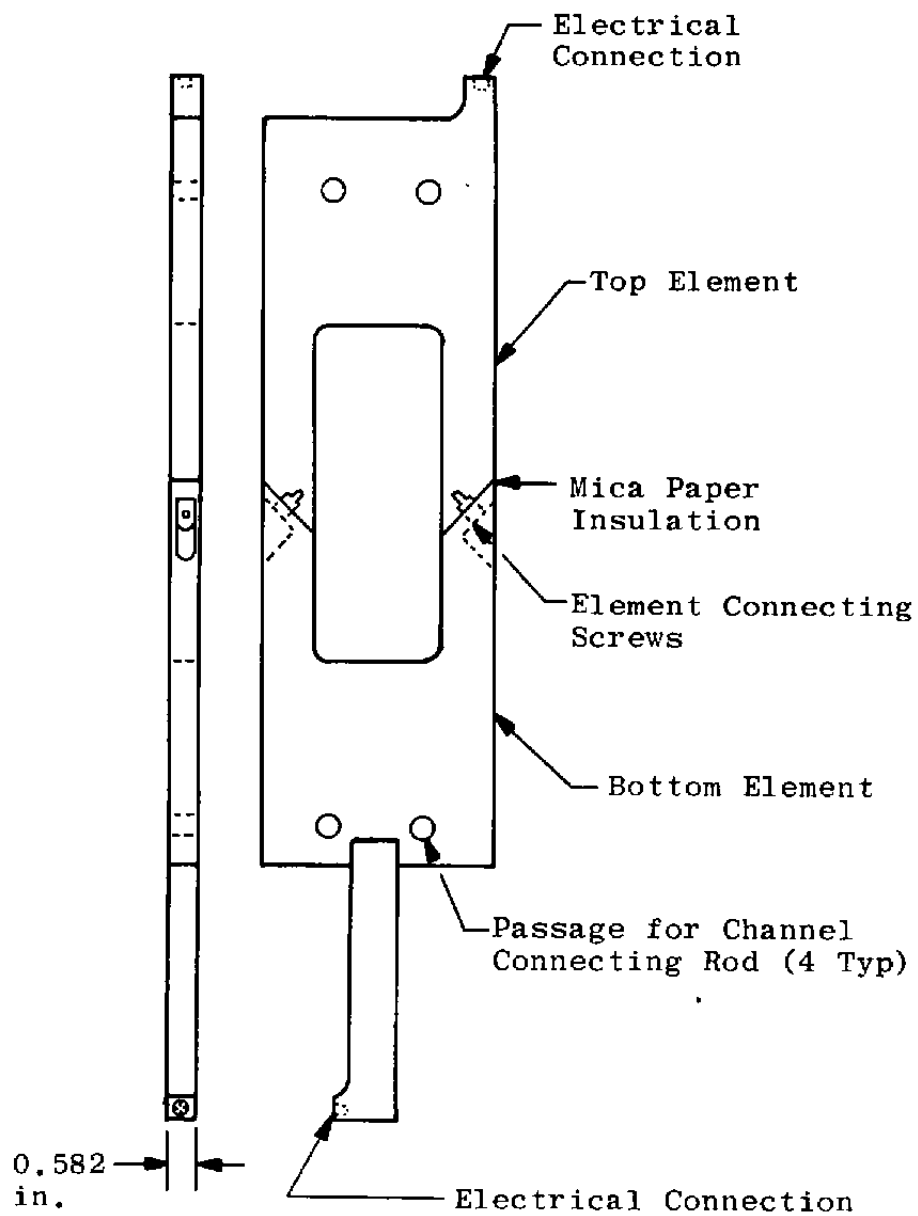
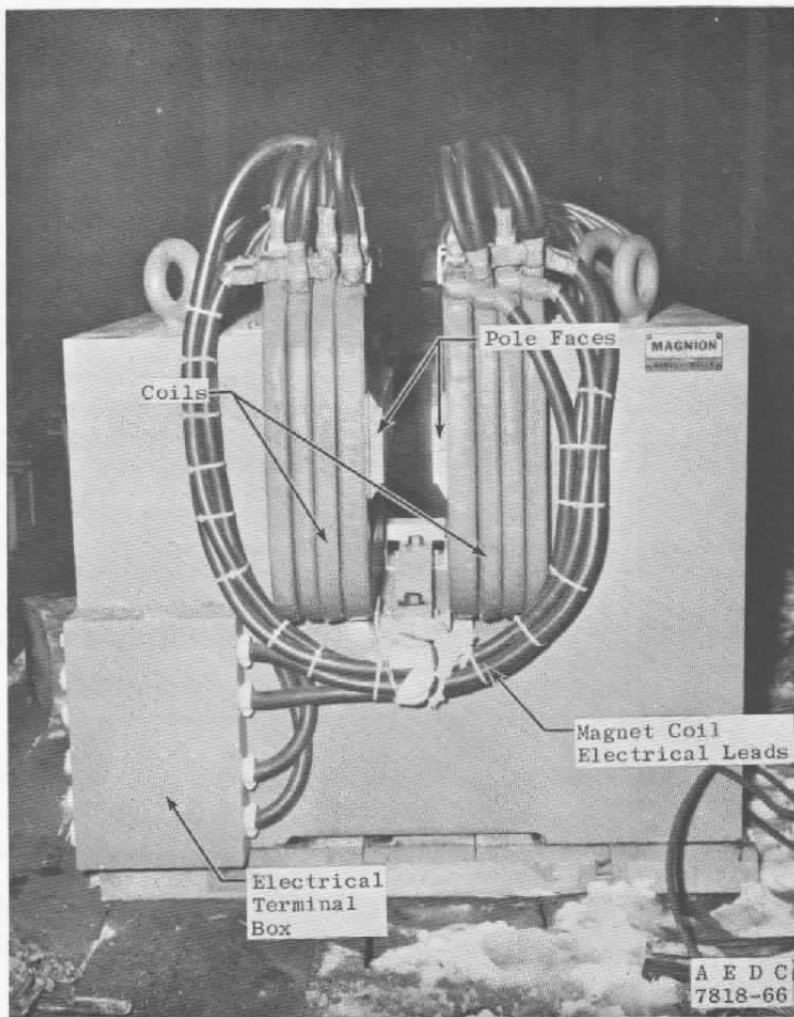
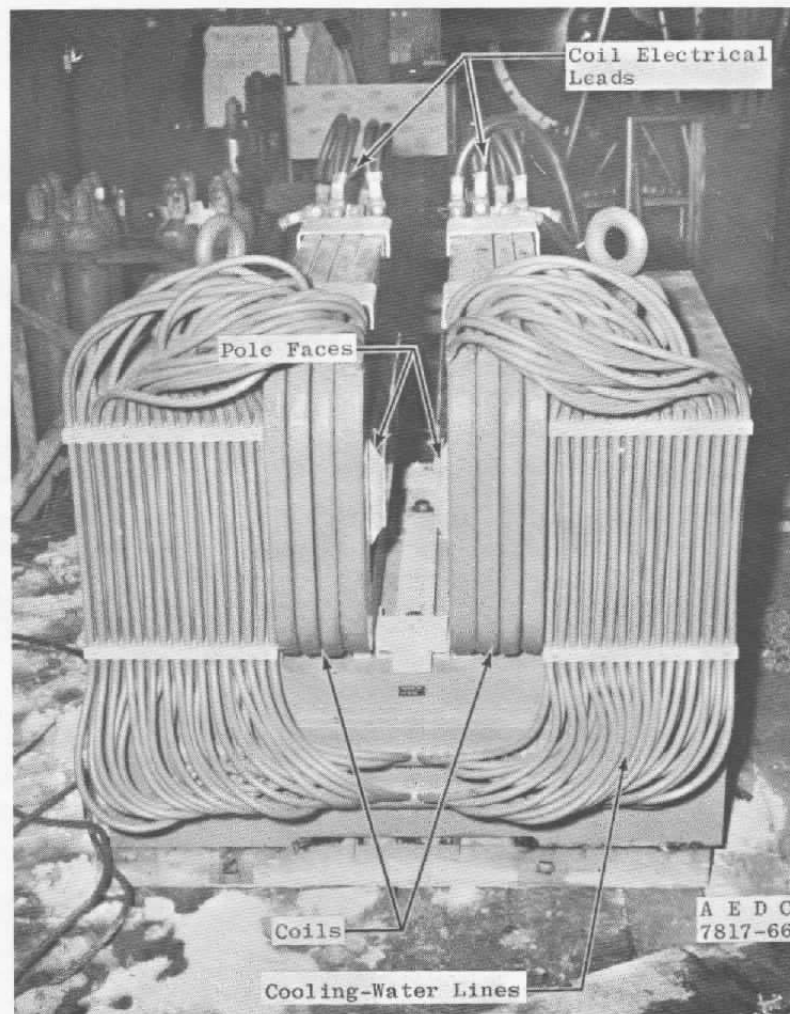


Fig. 4 Schematic of Typical Hall Channel Segment

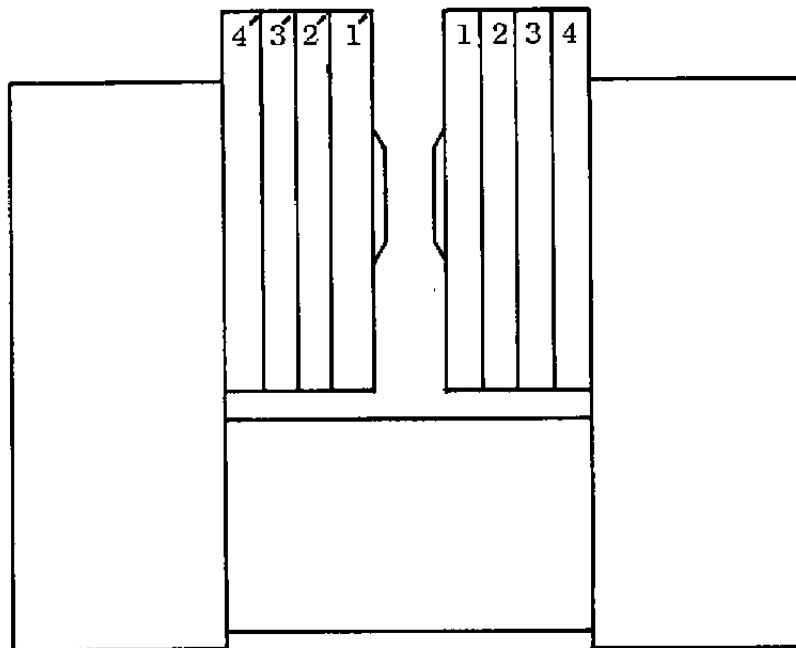


a. Photograph, Looking Upstream

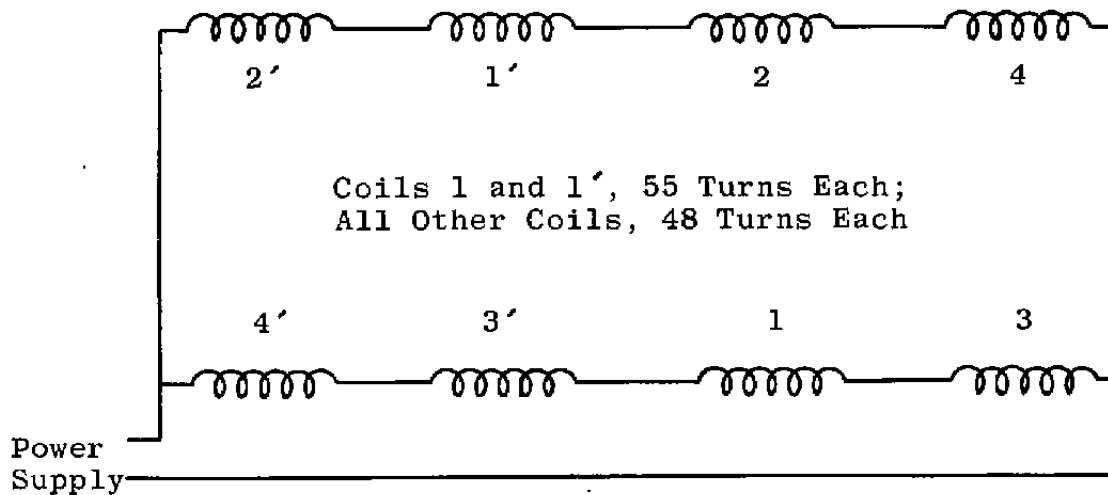


b. Photograph, Looking Downstream

Fig. 5 Electromagnet



Coil Locations
(Looking Upstream)



c. Coil Electrical Schematic
Fig. 5 Concluded

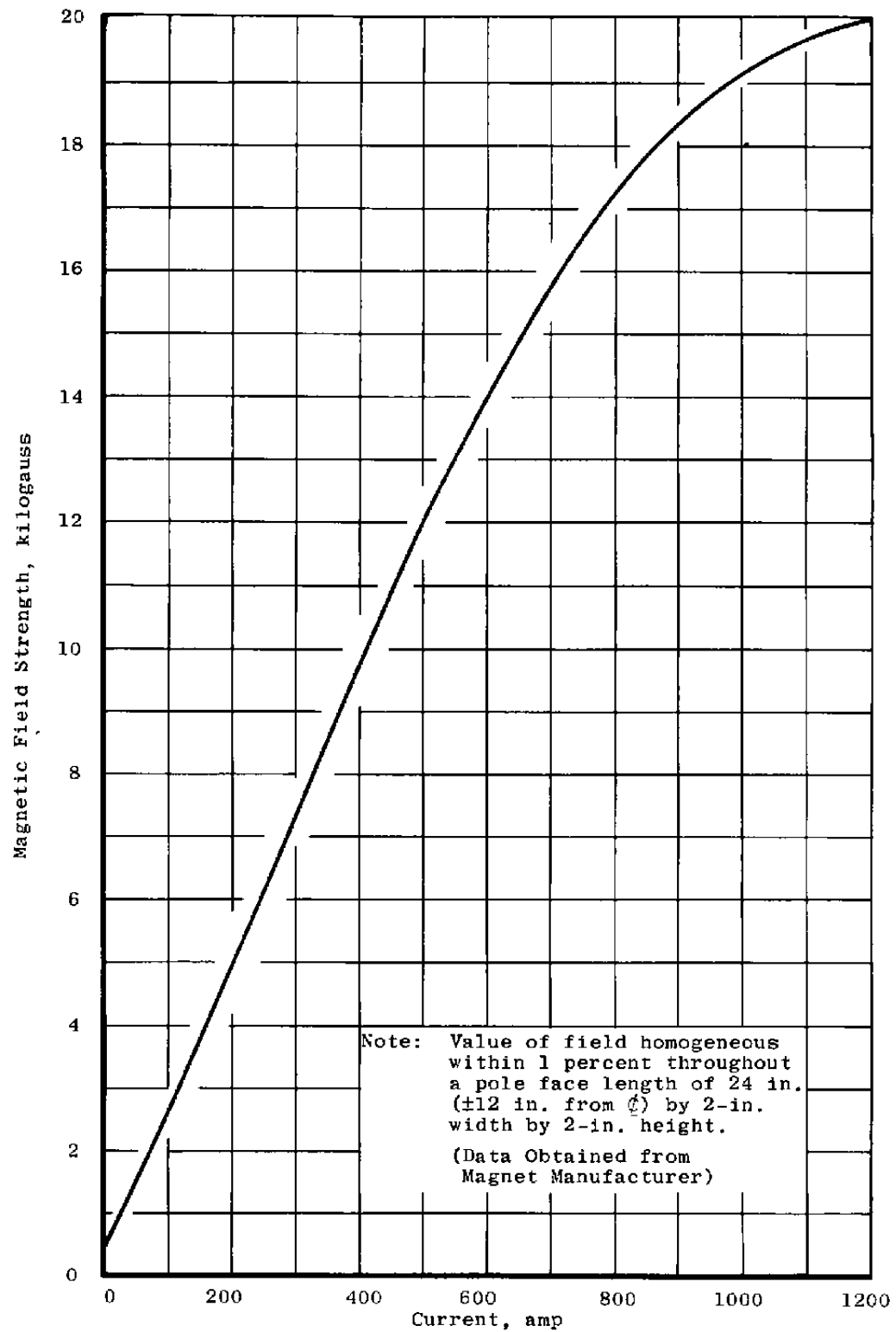


Fig. 6 Magnet Field Strength as a Function of Current

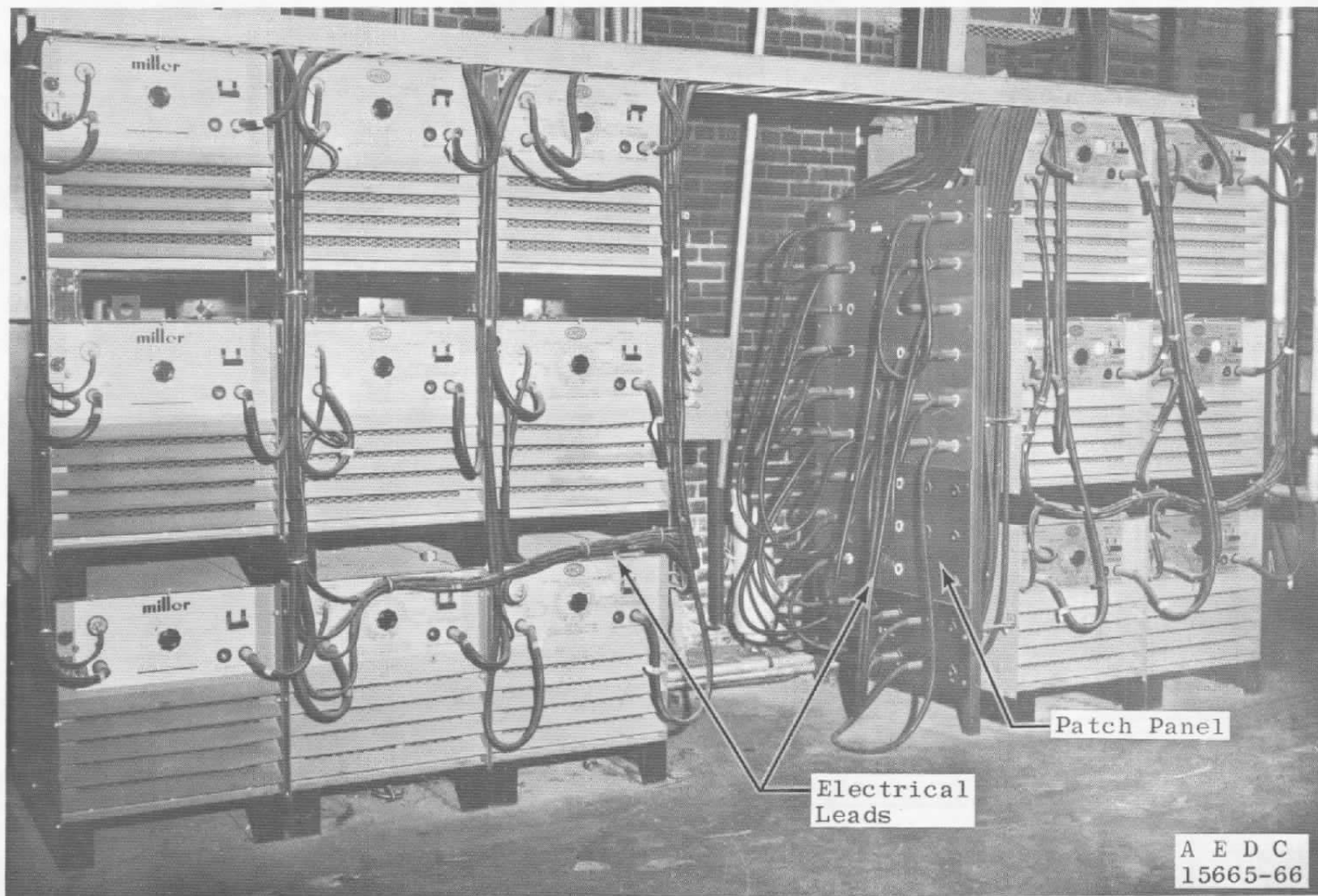
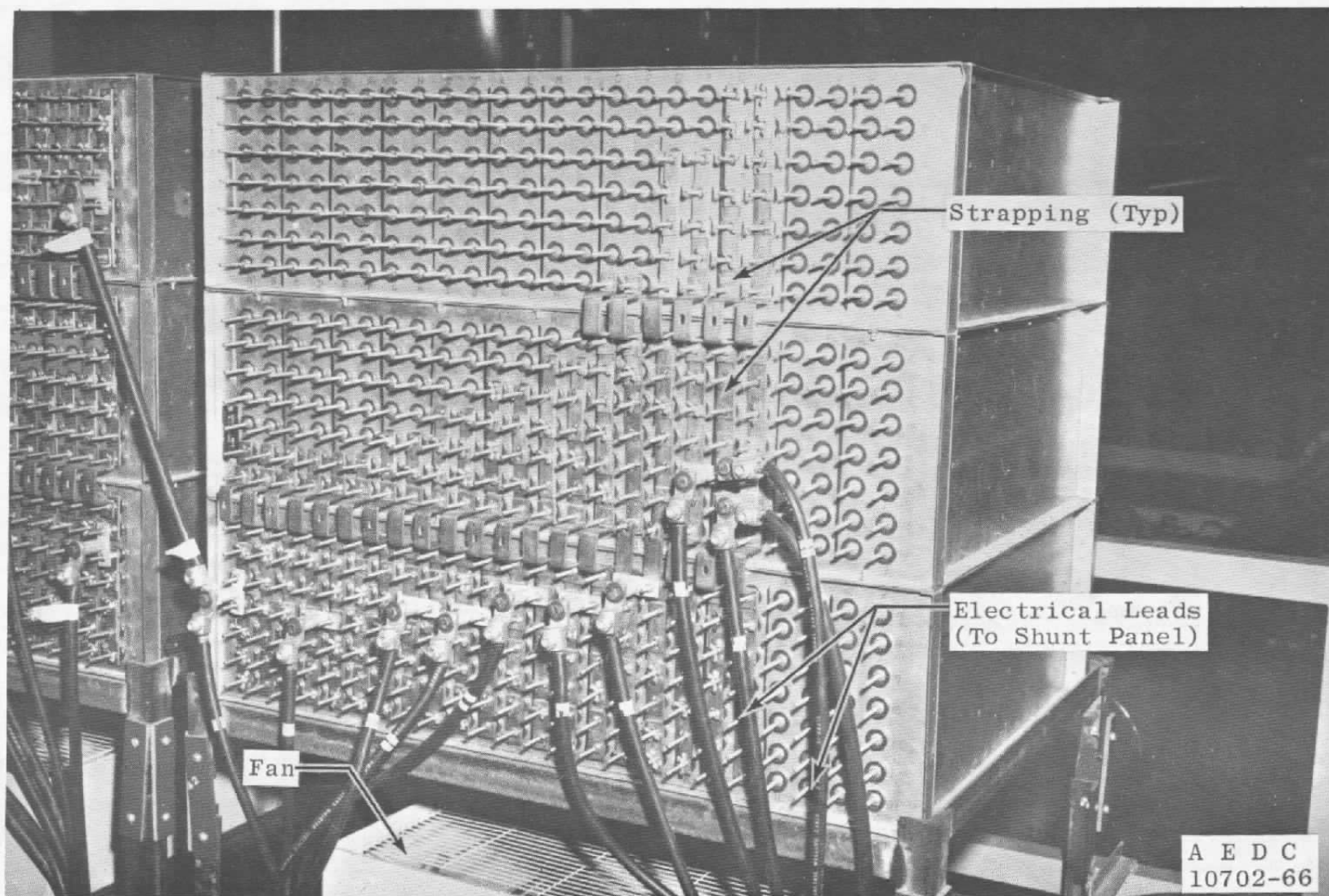
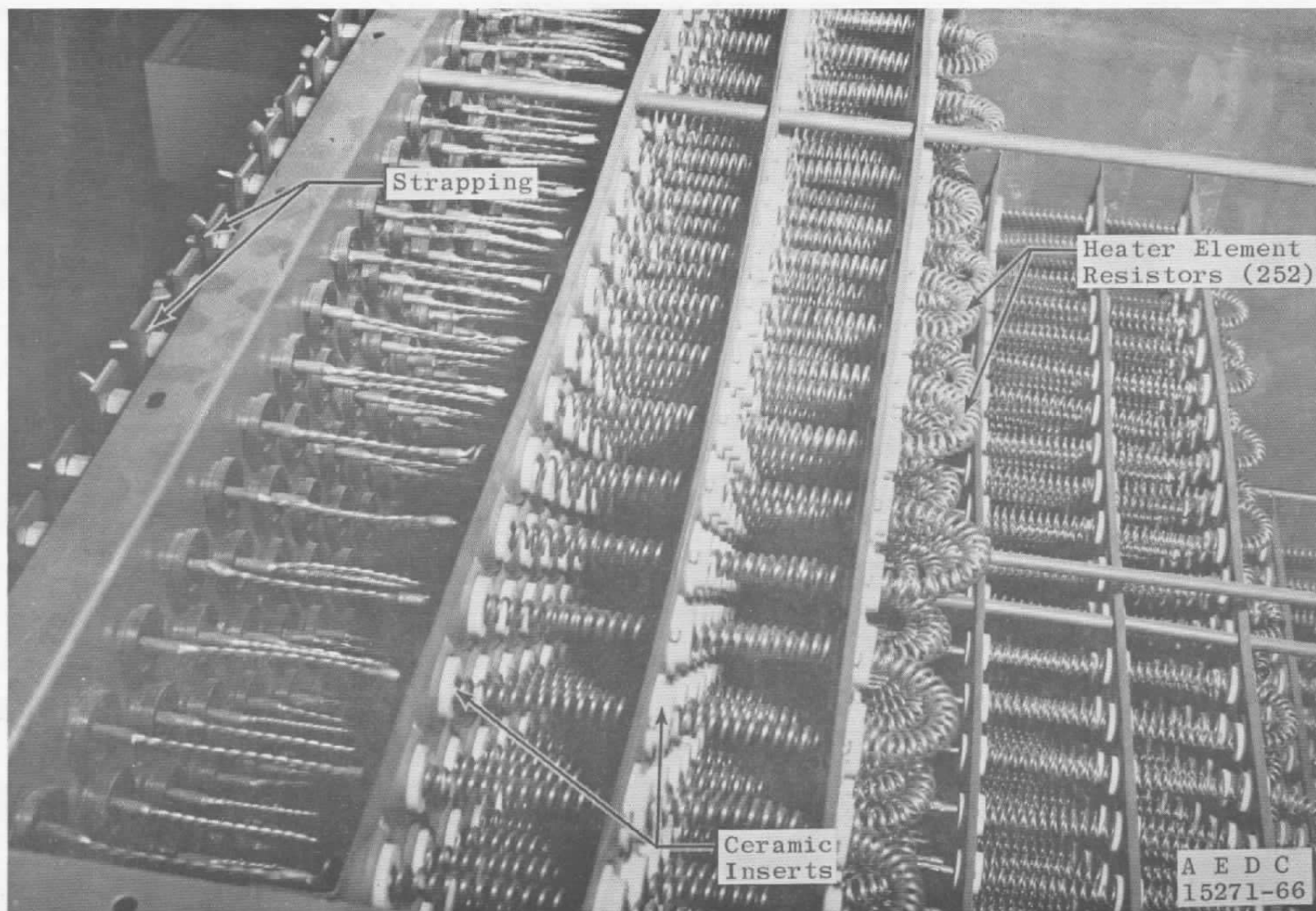


Fig. 7 Photograph of Magnet Power Supplies

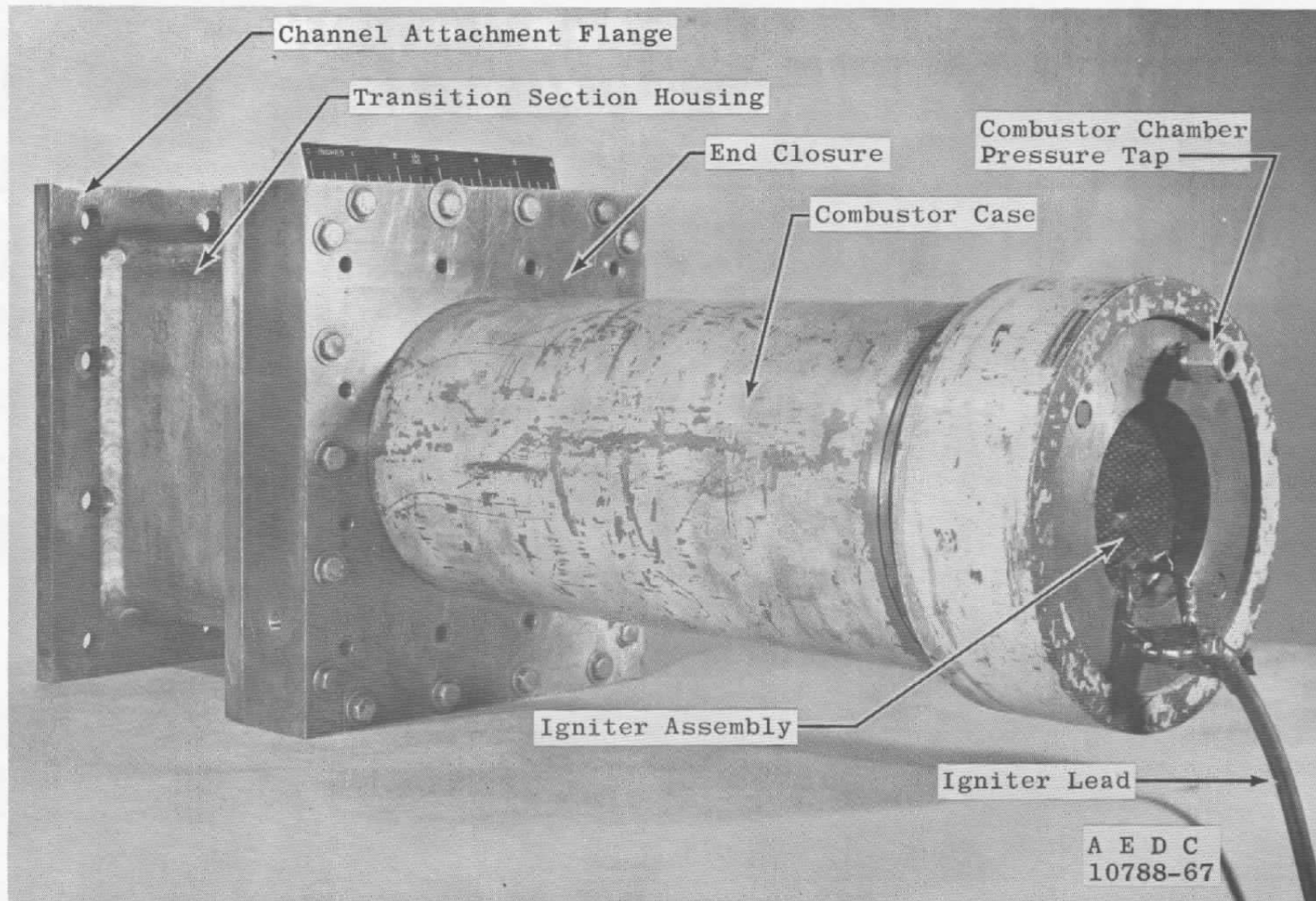


a. Front View

Fig. 8 Photographs of Load Bank Unit

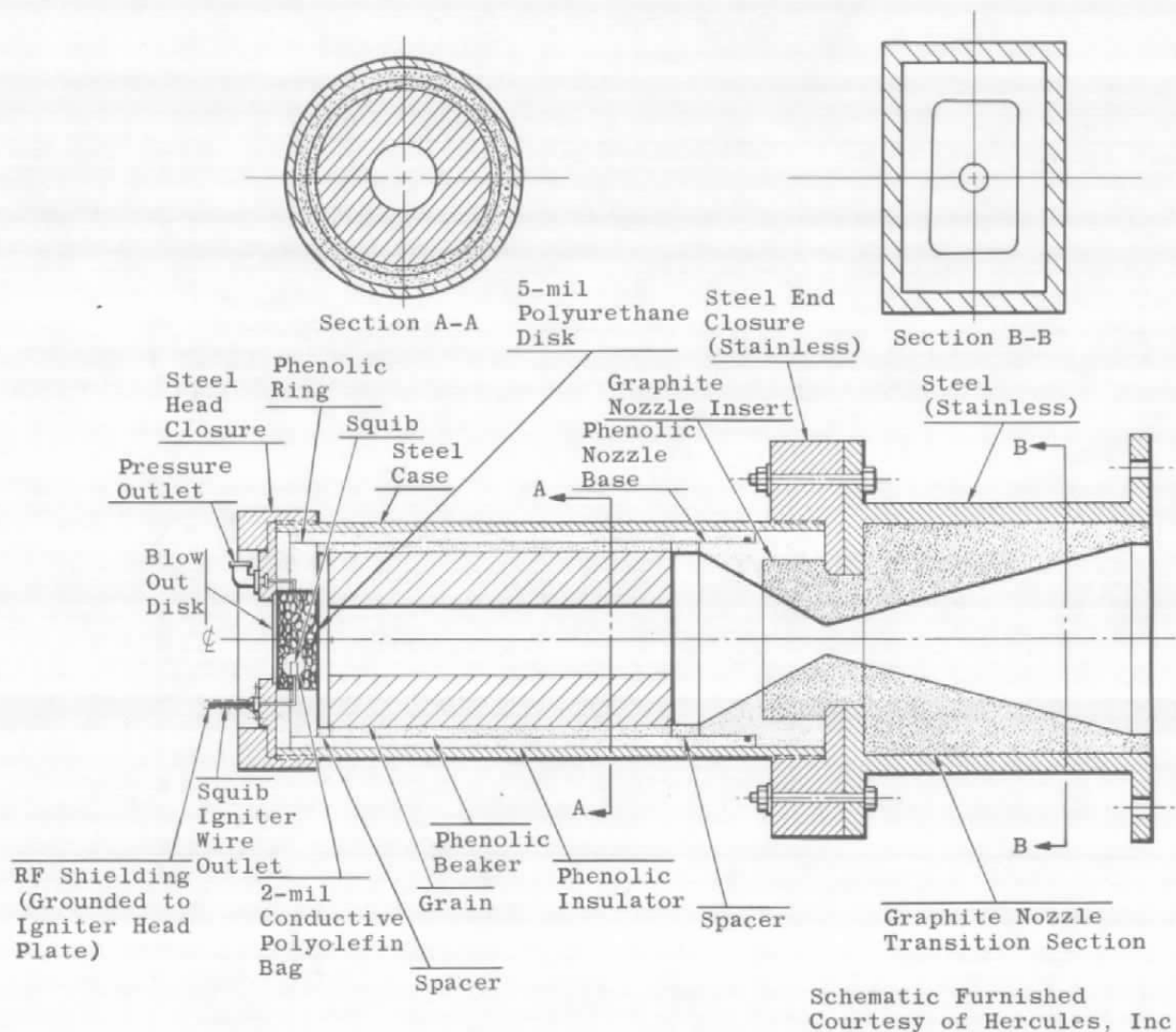


b. Top View
Fig. 8 Concluded

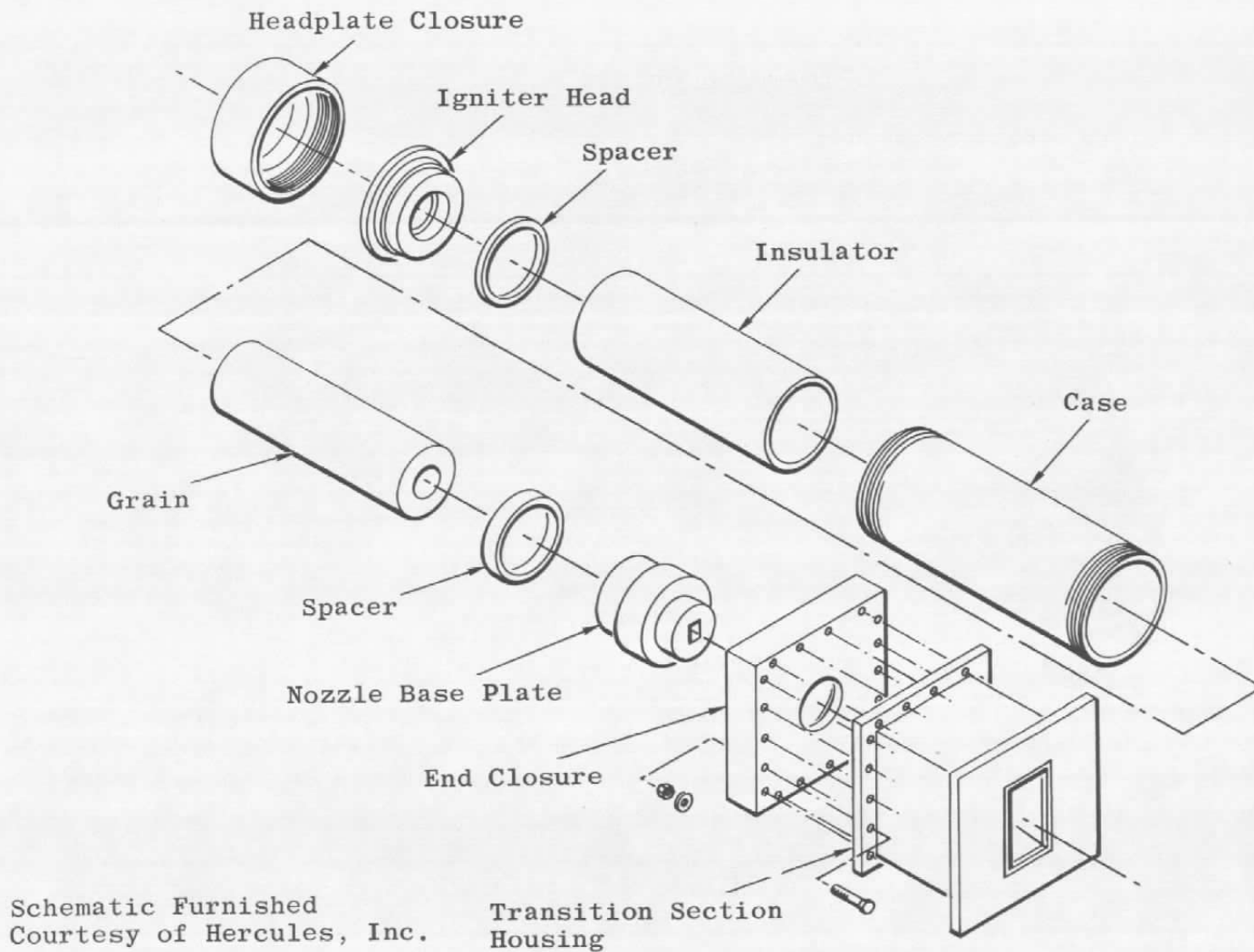


a. Photograph

Fig. 9 Combustor Assembly



b. Detailed Schematic
Fig. 9 Continued



c. Schematic of Assembly
Fig. 9 Concluded

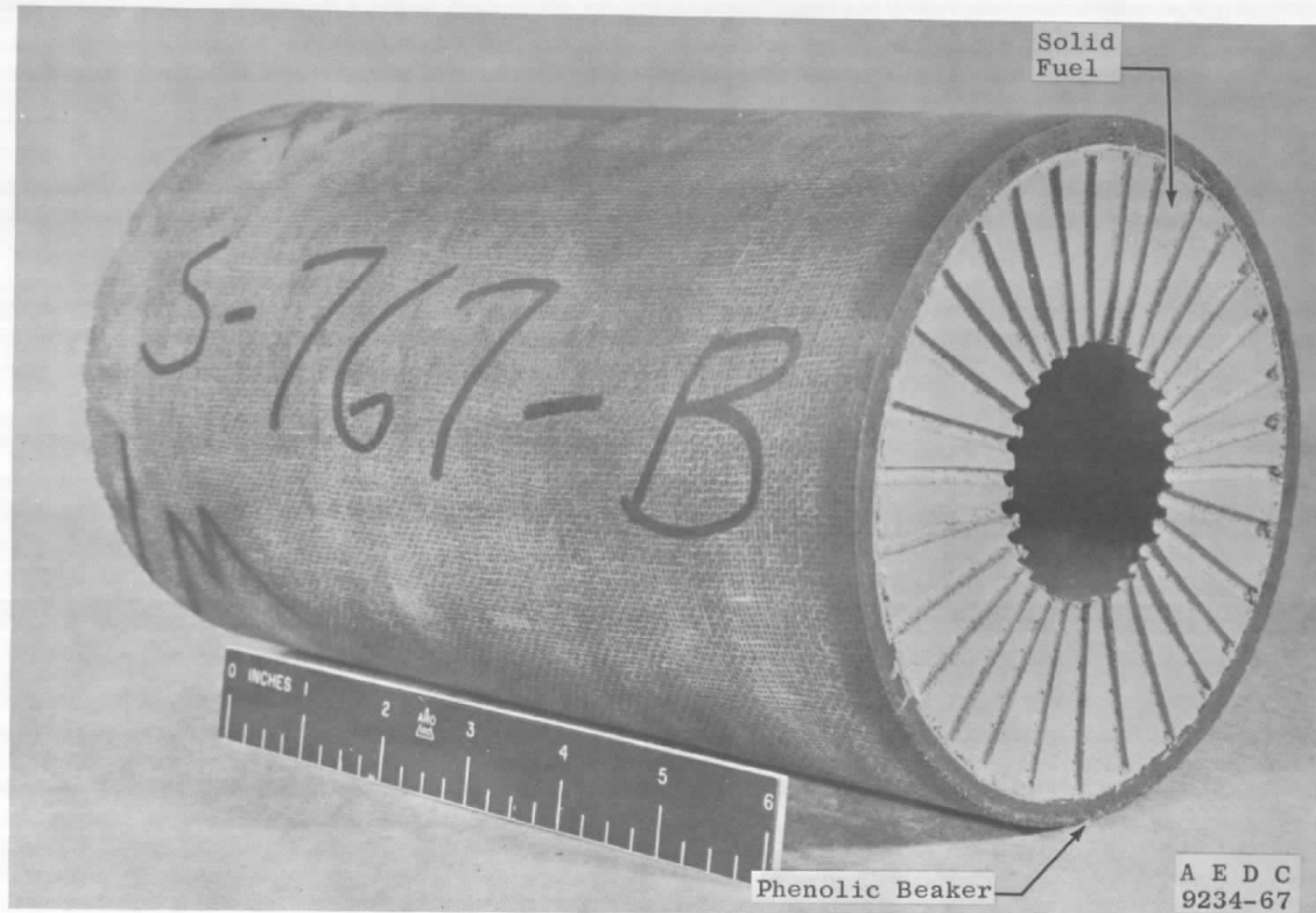
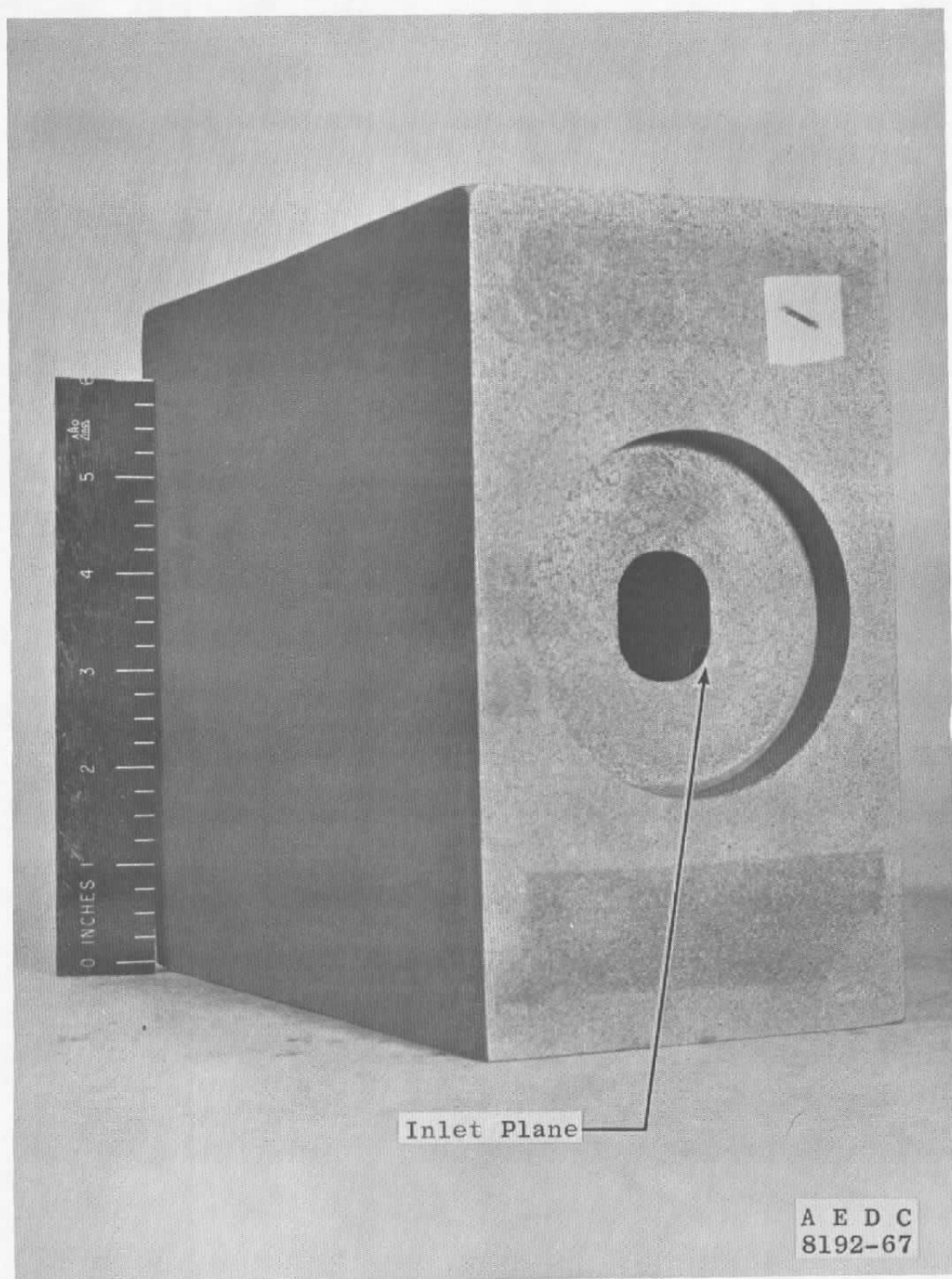
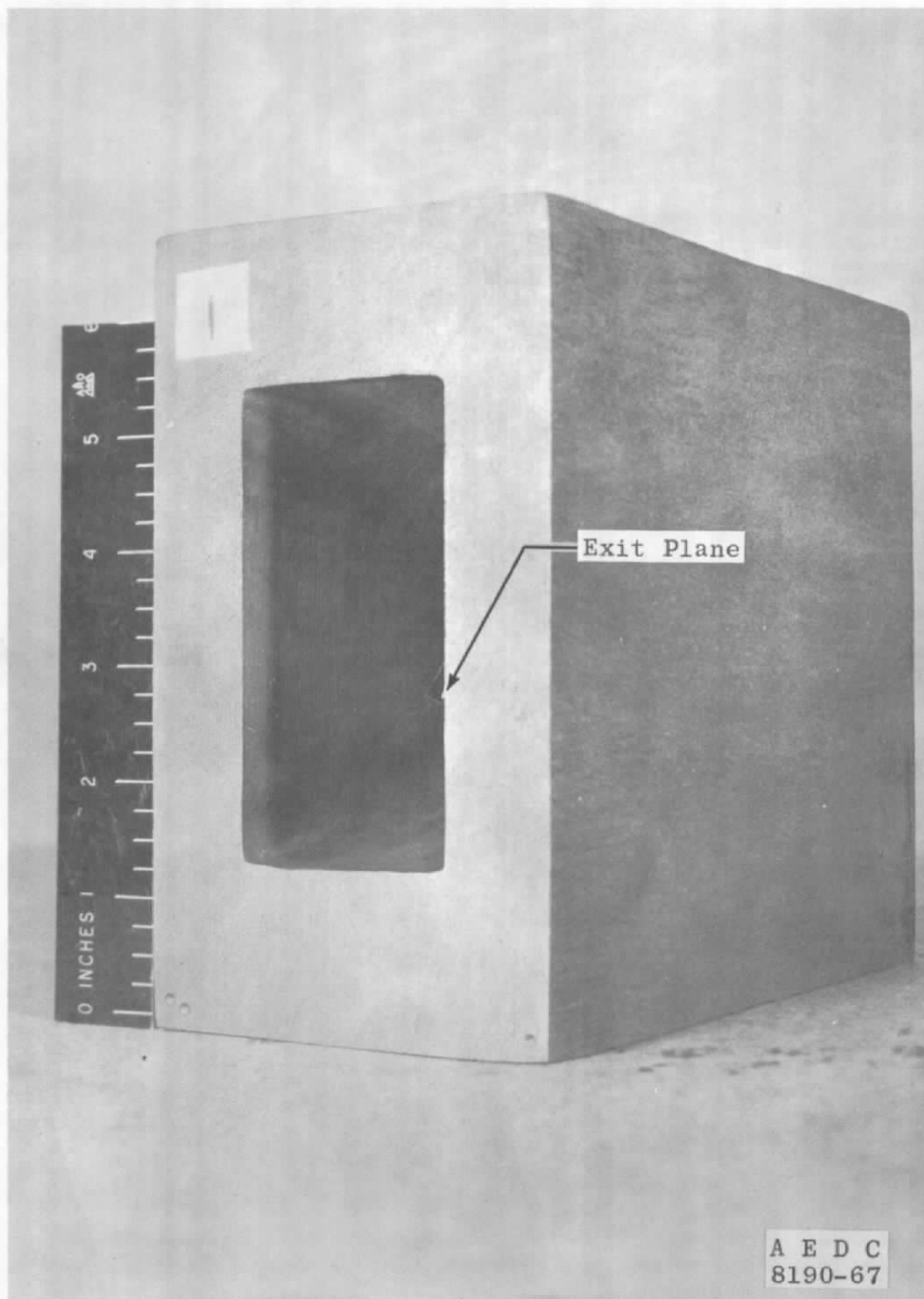


Fig. 10 Photograph of Solid-Fuel Grain

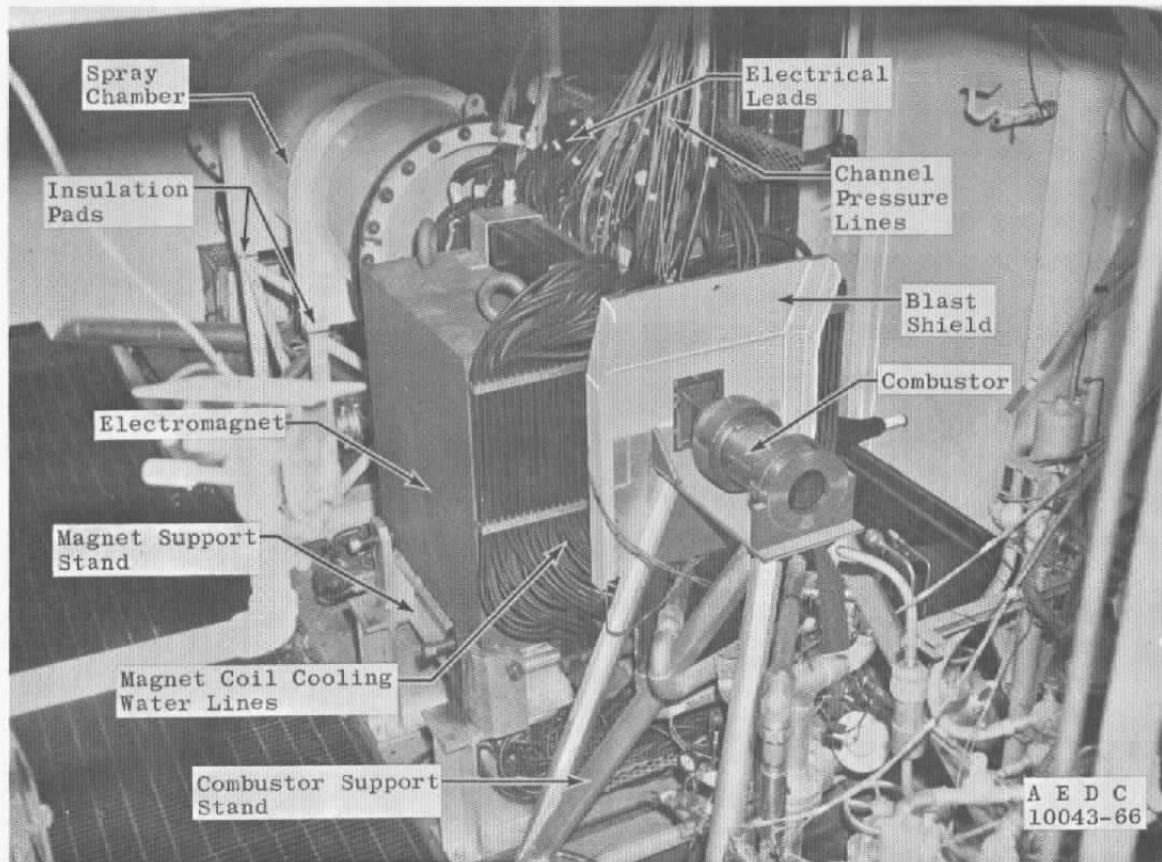


a. View Showing Inlet Plane

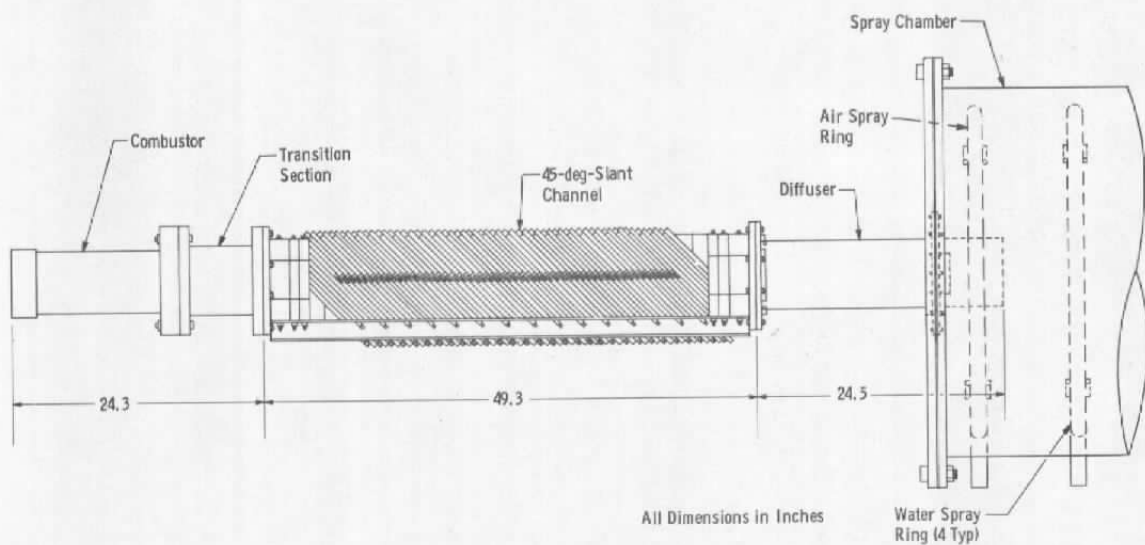
Fig. 11 Photographs of Graphite Nozzle Transition Section



b. View Showing Exit Plane
Fig. 11 Concluded



a. Photograph



b. Schematic

Fig. 12 Installation of MHD Generator Assembly in Propulsion Research Area (R-2C-4)

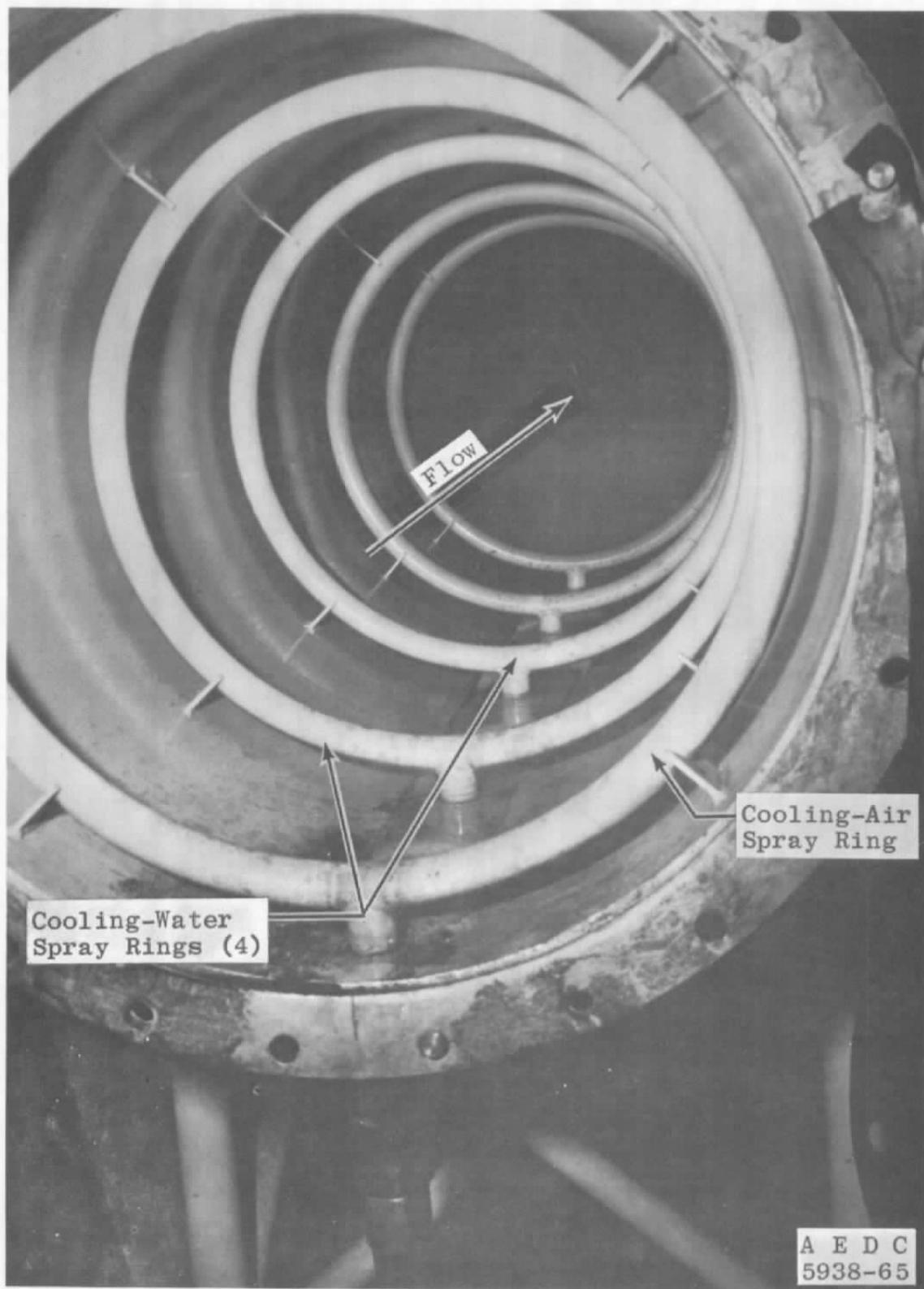


Fig. 13 Photograph of Spray Chamber

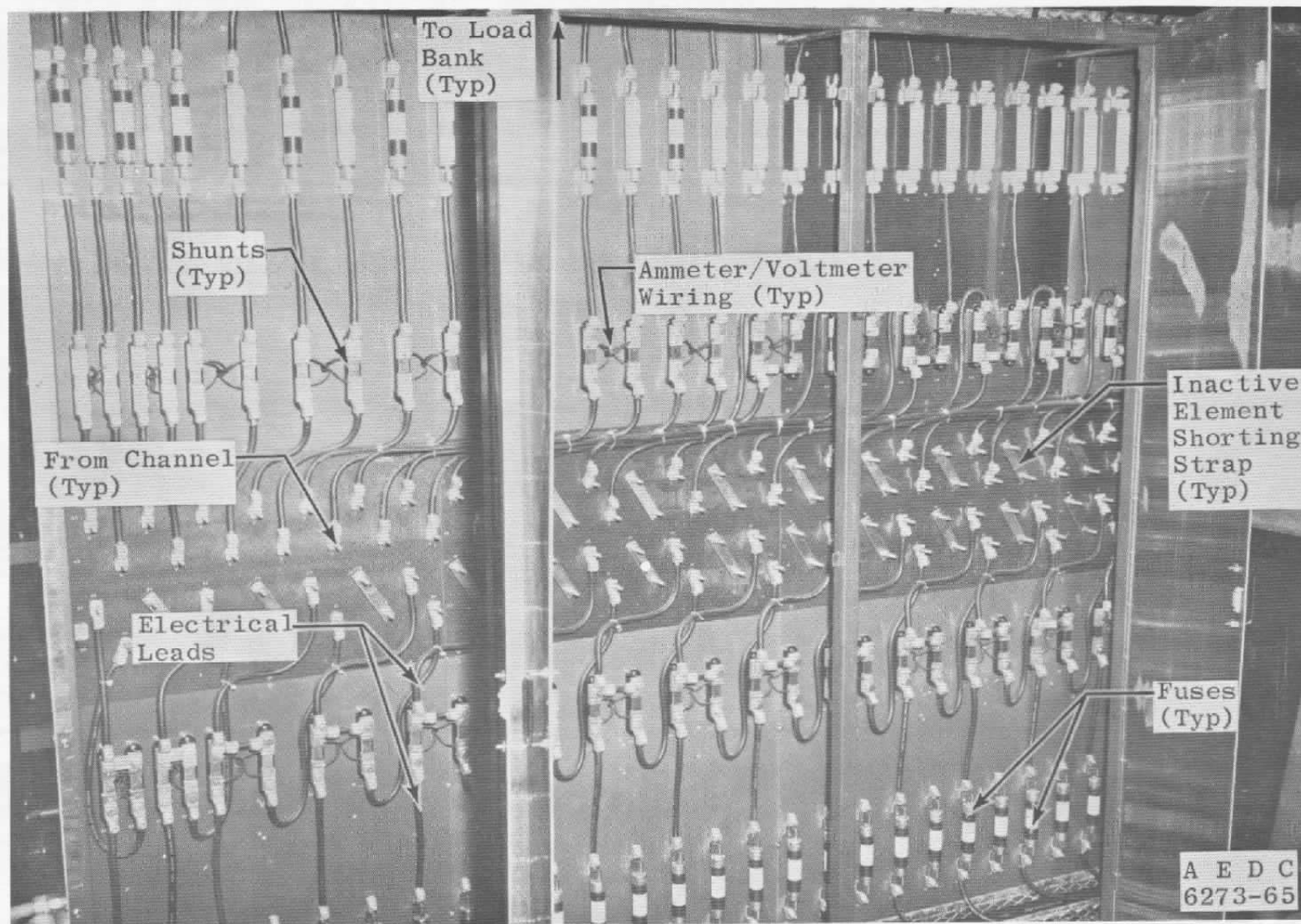
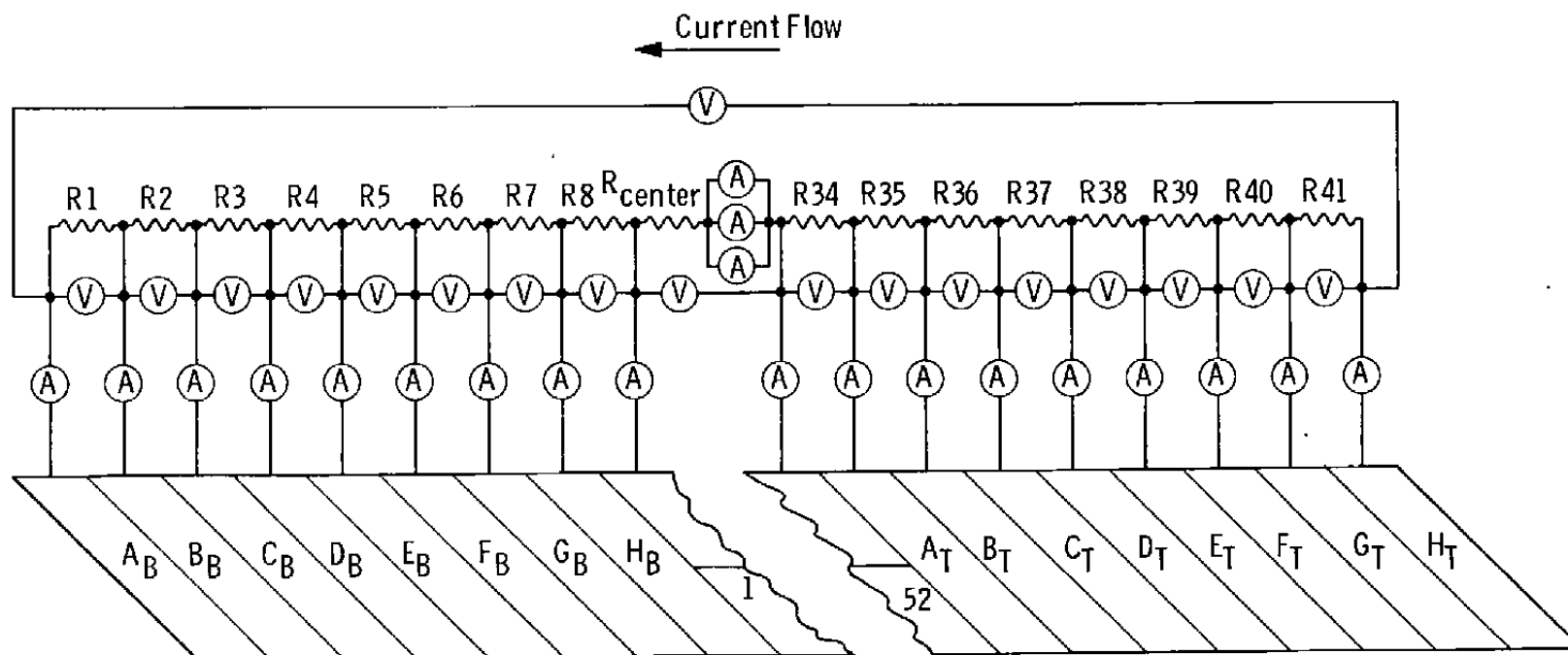


Fig. 14 Photograph of Shunt Panel

32

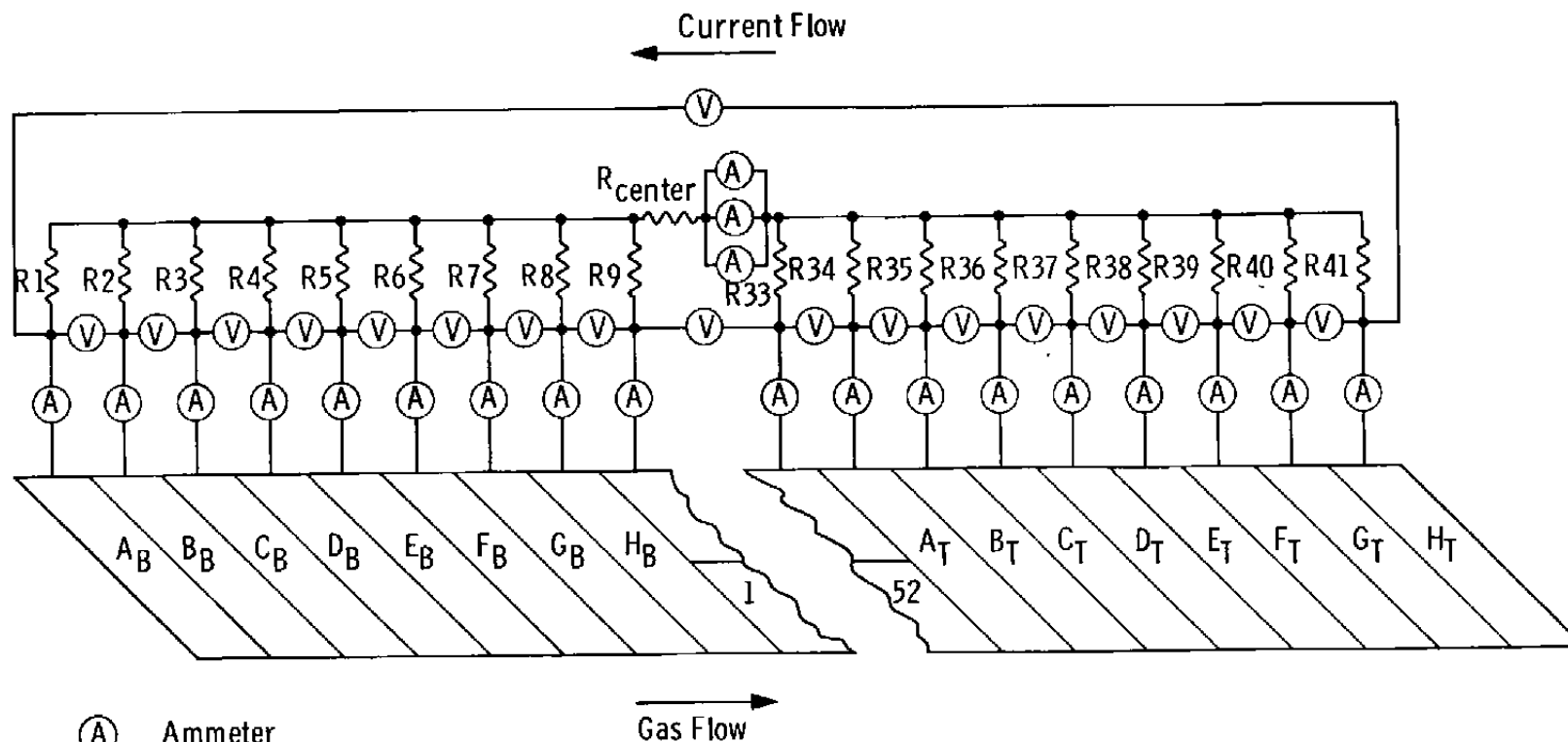


- (A) Ammeter
 (V) Voltmeter
 R Load Resistor

- Notes: 1. Partial End Electrodes Denoted with Letter Designation
 2. All Complete Electrodes (Designated with Numbers) Were Externally Shorted Top-to-Bottom. Electrodes Instrumented for Top-to-Bottom Current Flow Measurements Are Shown in Table IVb.
 3. Normal Magnet Field Direction from Right to Left Looking Downstream

a. Firings 71 through 76

Fig. 15 Schematic of Electrical Circuit for 45-deg-Slant Channel Power Generation Firings

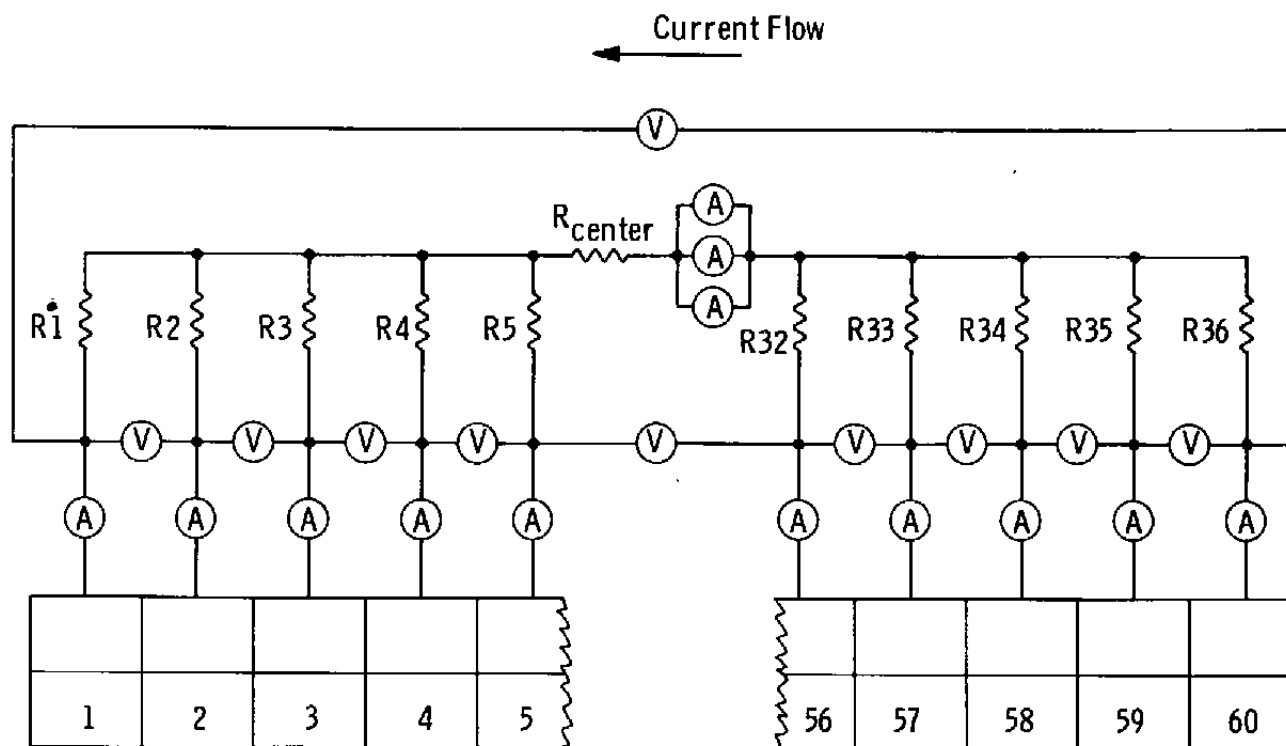


- (A) Ammeter
 (V) Voltmeter
 R Load Resistor

- Notes: 1. Partial End Electrodes Denoted with Letter Designation
 2. All Complete Electrodes (Designated with Numbers) Were Externally Shorted Top-to-Bottom. Electrodes Instrumented for Top-to-Bottom Current Flow Measurements Are Shown in Table IVb.
 3. Normal Magnet Field Direction from Right to Left Looking Downstream

b. Firings 77 through 83

Fig. 15 Concluded



- (A) Ammeter
(V) Voltmeter
R Load Resistor

- Notes: 1. All Electrodes Were Externally Shorted Top-to-Bottom. Electrodes Instrumented for Top-to-Bottom Current Flow Measurements Are Shown in Table Vb.
2. Normal Magnet Field Direction from Right to Left Looking Downstream

Fig. 16 Schematic of Electrical Circuit for Hall Channel Power Generation Firings

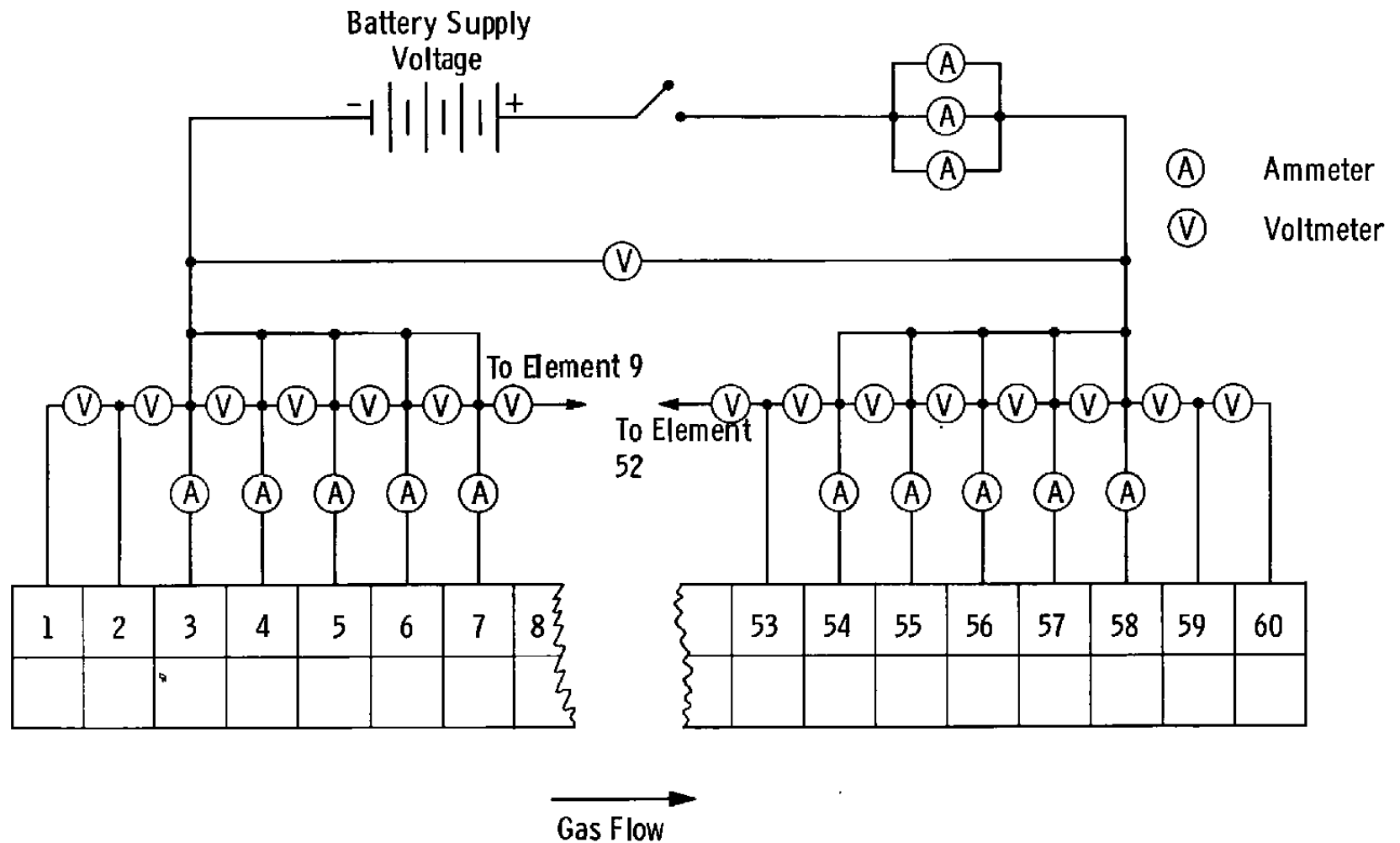


Fig. 17 Schematic of Electrical Circuit for Hall Channel Conductivity Measurement Firings

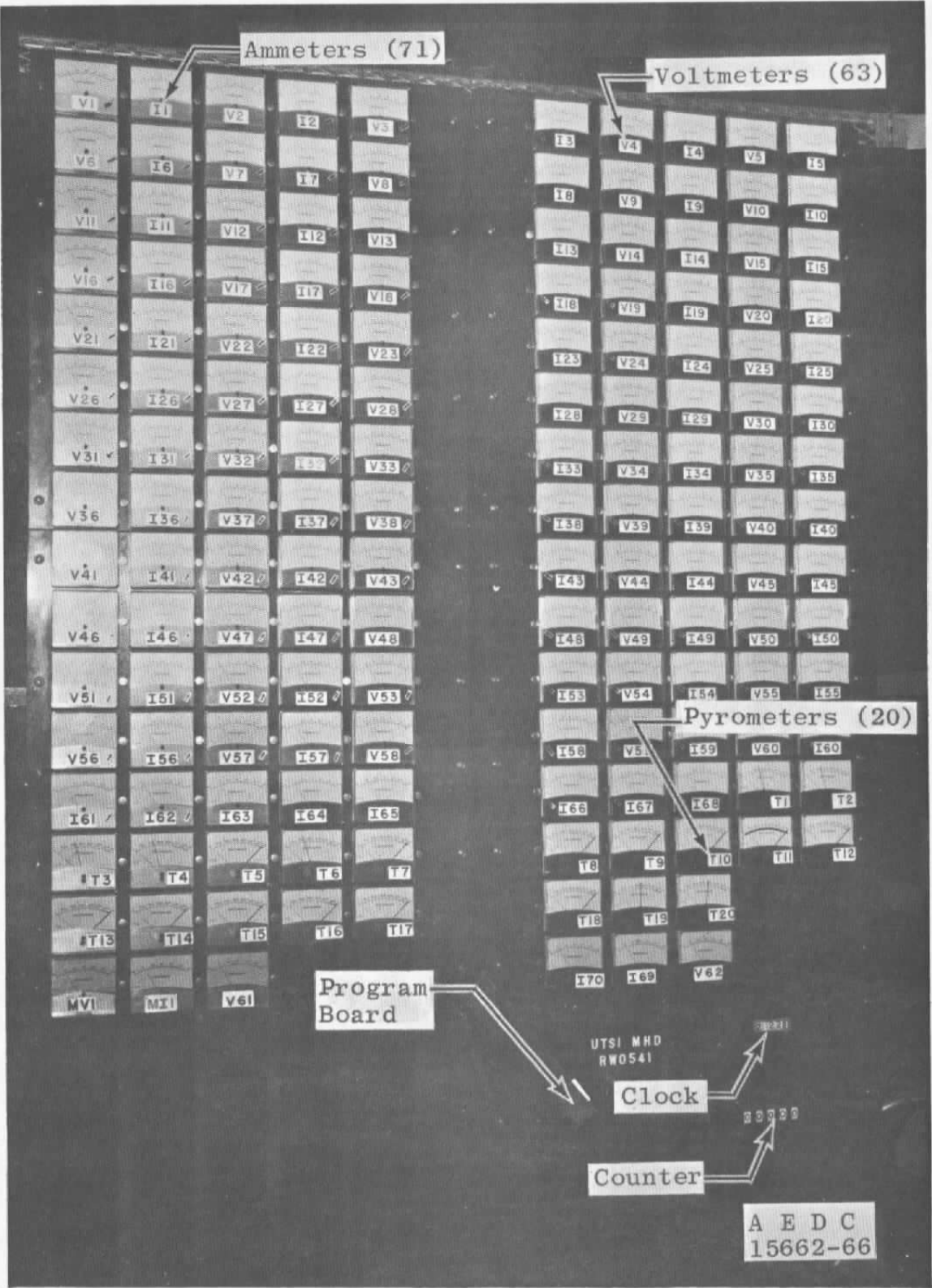


Fig. 18 Photograph of Meter Panel

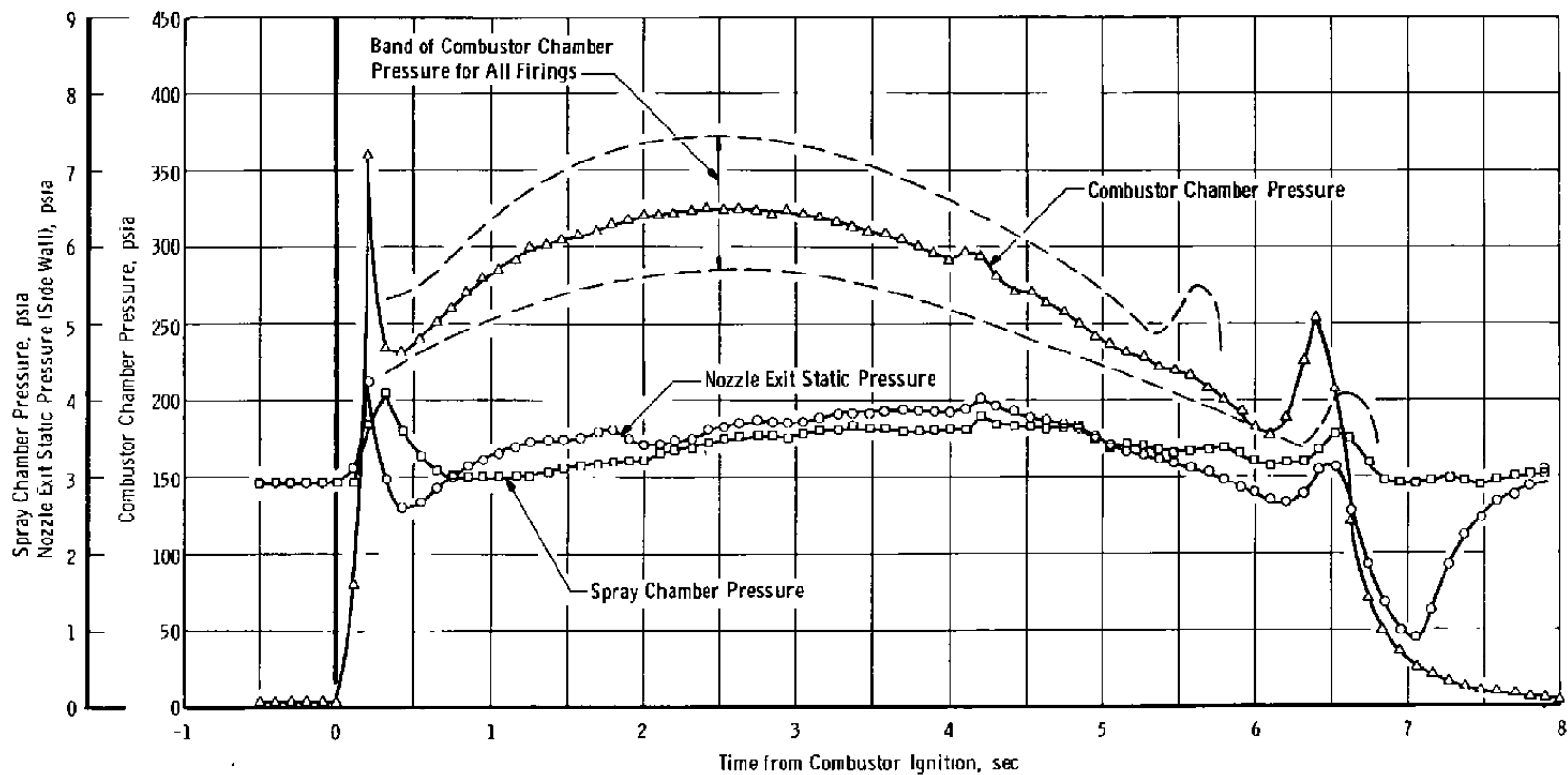


Fig. 19 Variation in Combustor Chamber Pressure, Nozzle Exit Side Wall Static Pressure, and Spray Chamber Pressure during a Typical Power Generation Firing

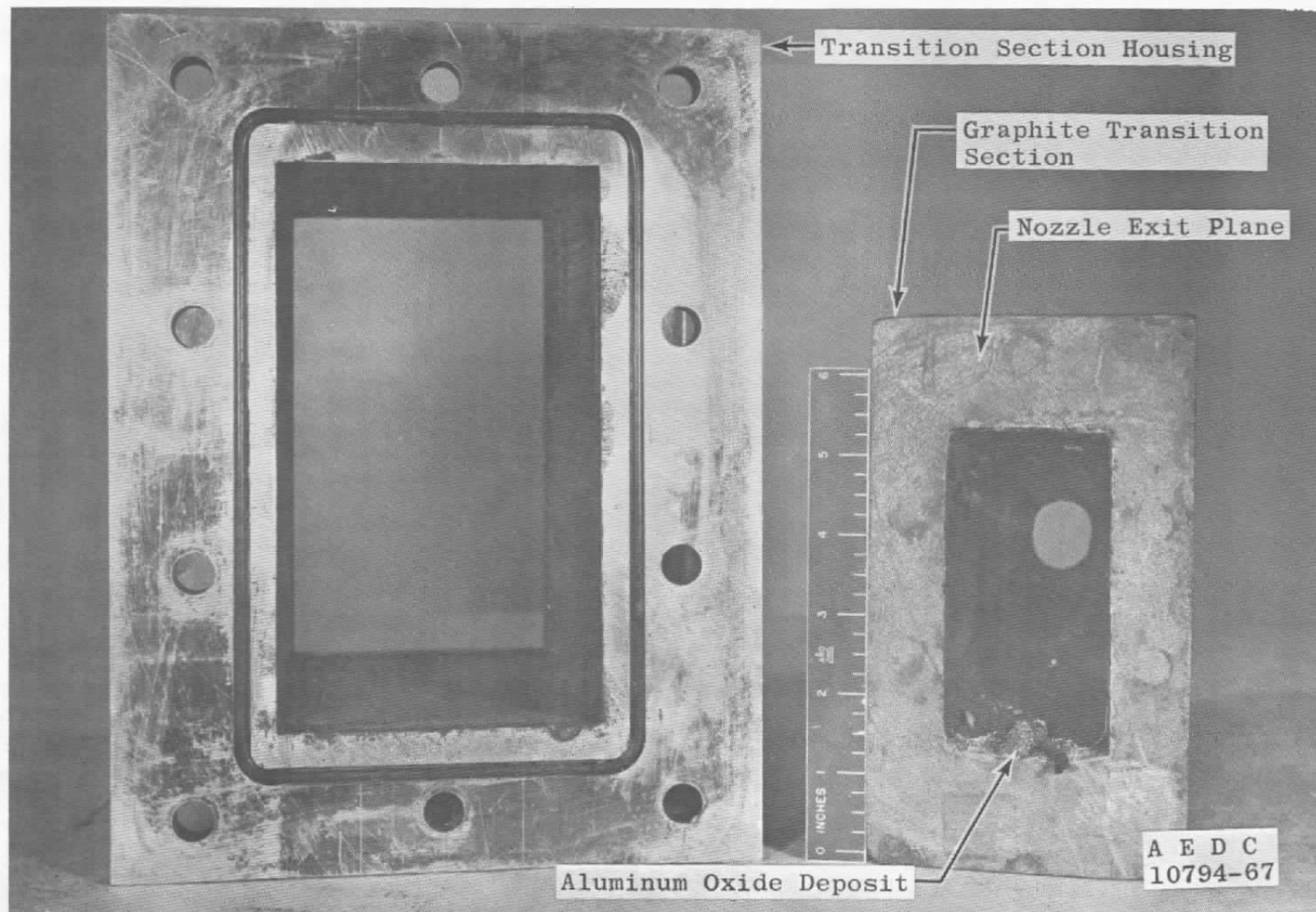


Fig. 20 Typical Post-Fire Photograph of Combustor Exhaust Nozzle Showing Aluminum Oxide Deposit, View Looking Upstream

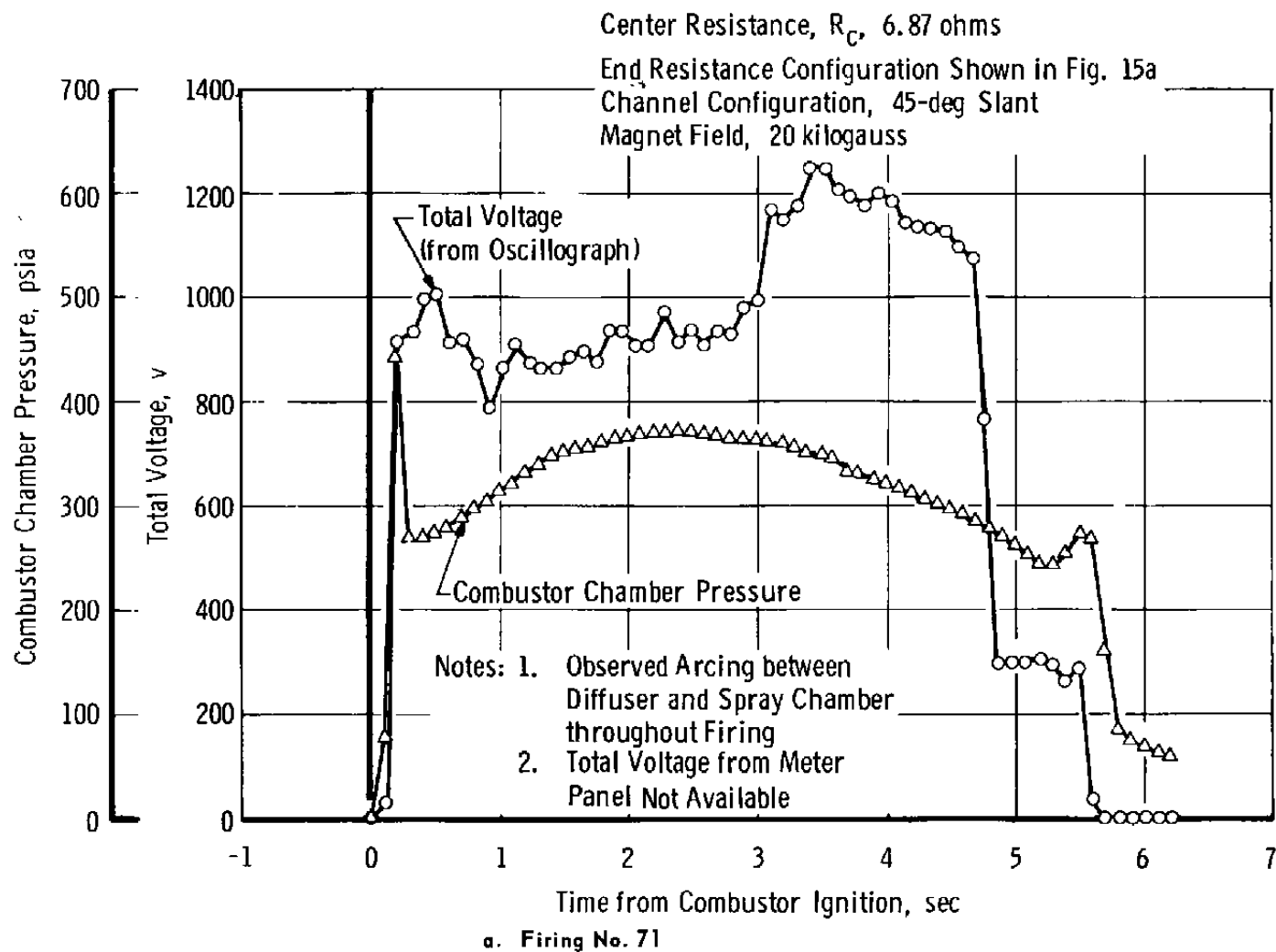
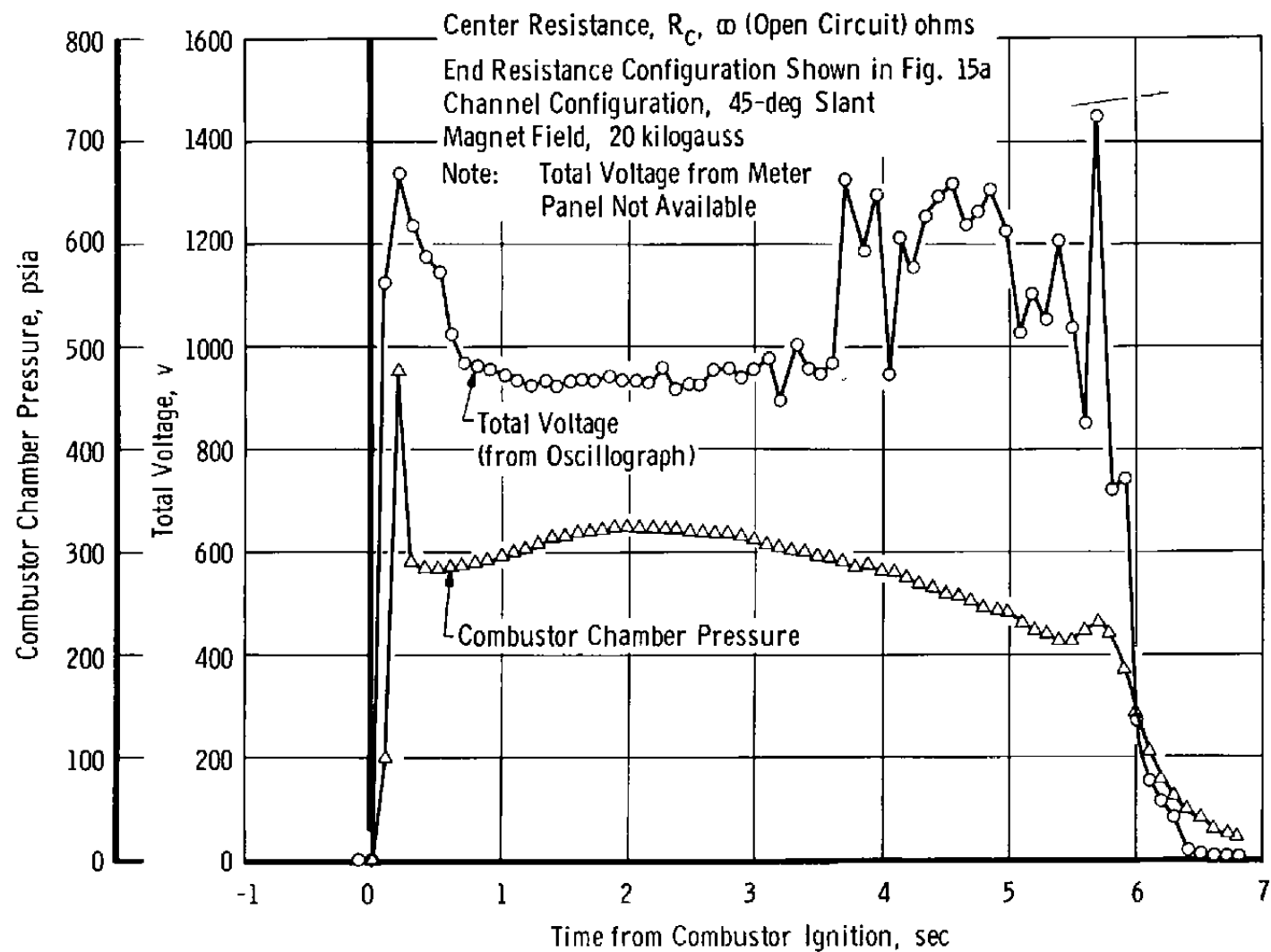


Fig. 21 Variation in Total Channel Voltage and Combustor Chamber Pressure during 45-deg-Slant Wall Channel Power Generation Firings



b. Firing No. 72

Fig. 21 Continued

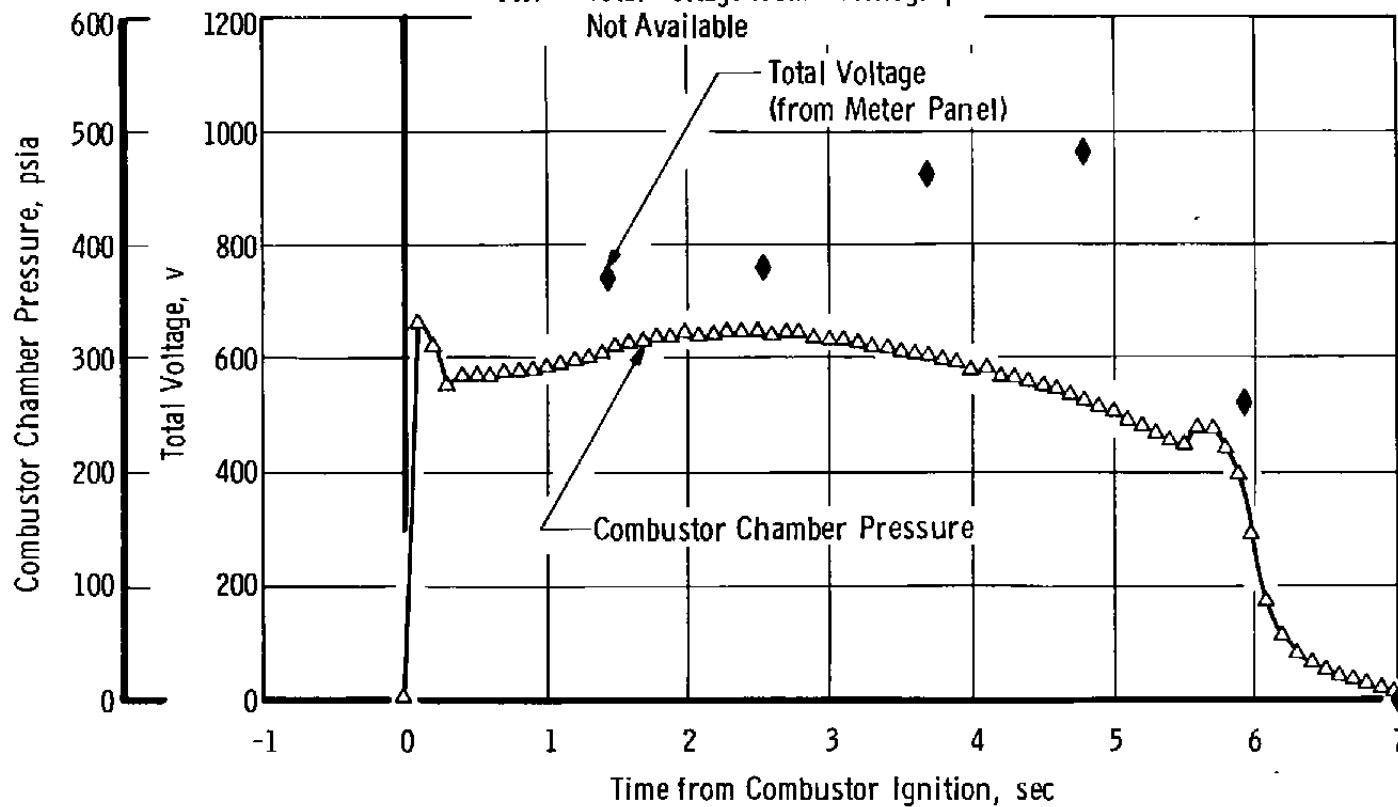
Center Resistance, R_C , 6.86 ohms

End Resistance Configuration Shown in Fig. 15a

Channel Configuration, 45-deg Slant

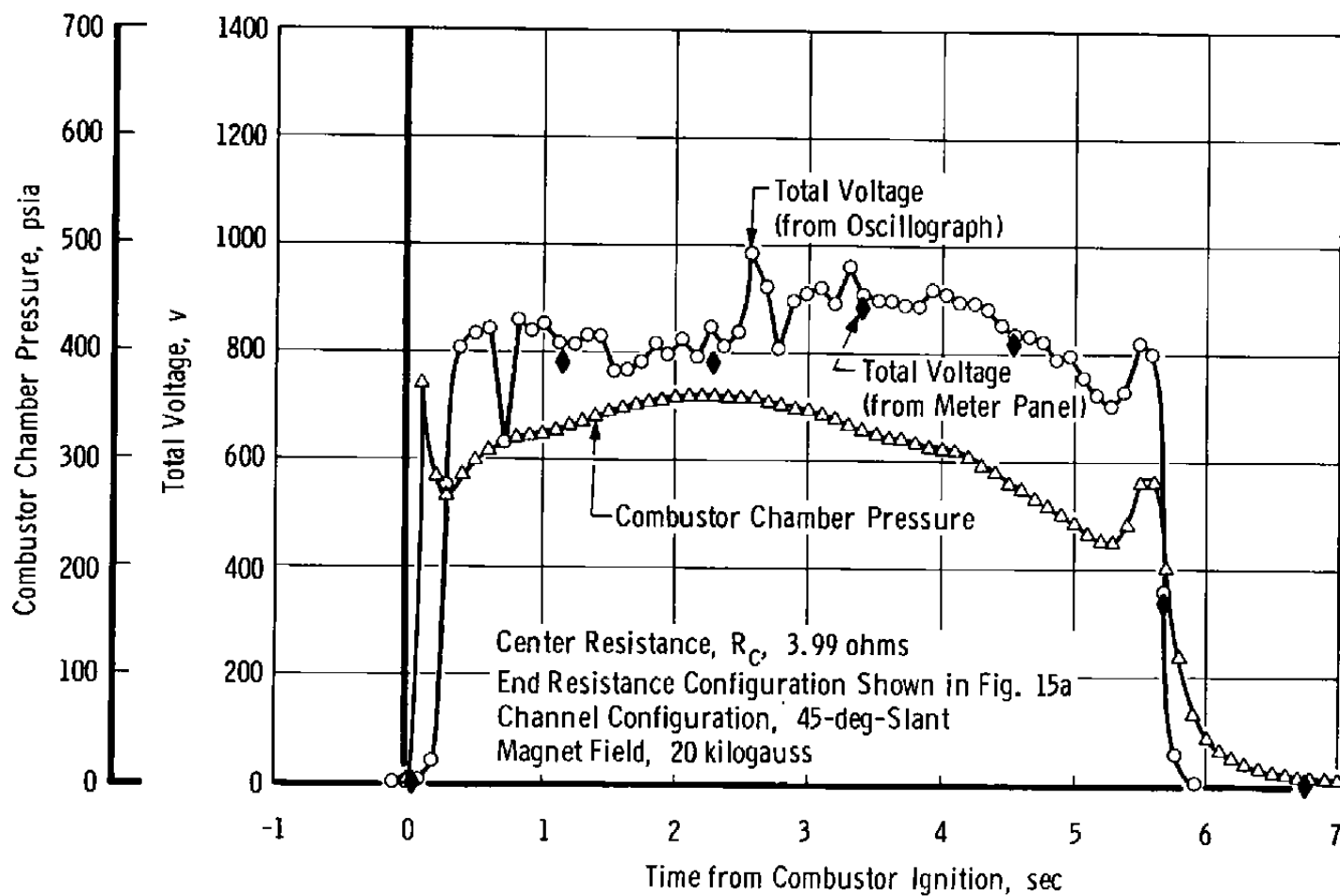
Magnet Field, 20 kilogauss

Note: Total Voltage from Oscillograph
Not Available



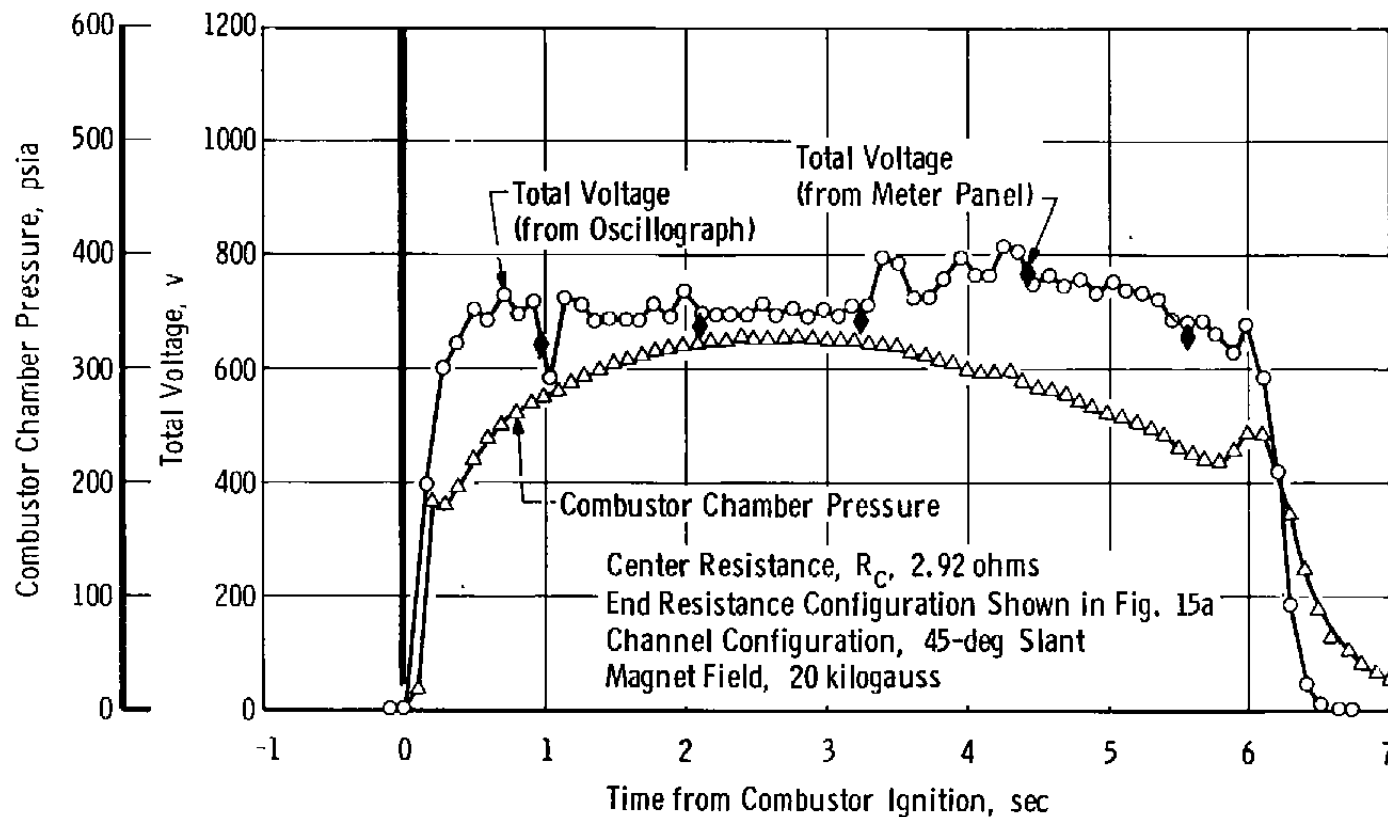
c. Firing No. 73

Fig. 21 Continued



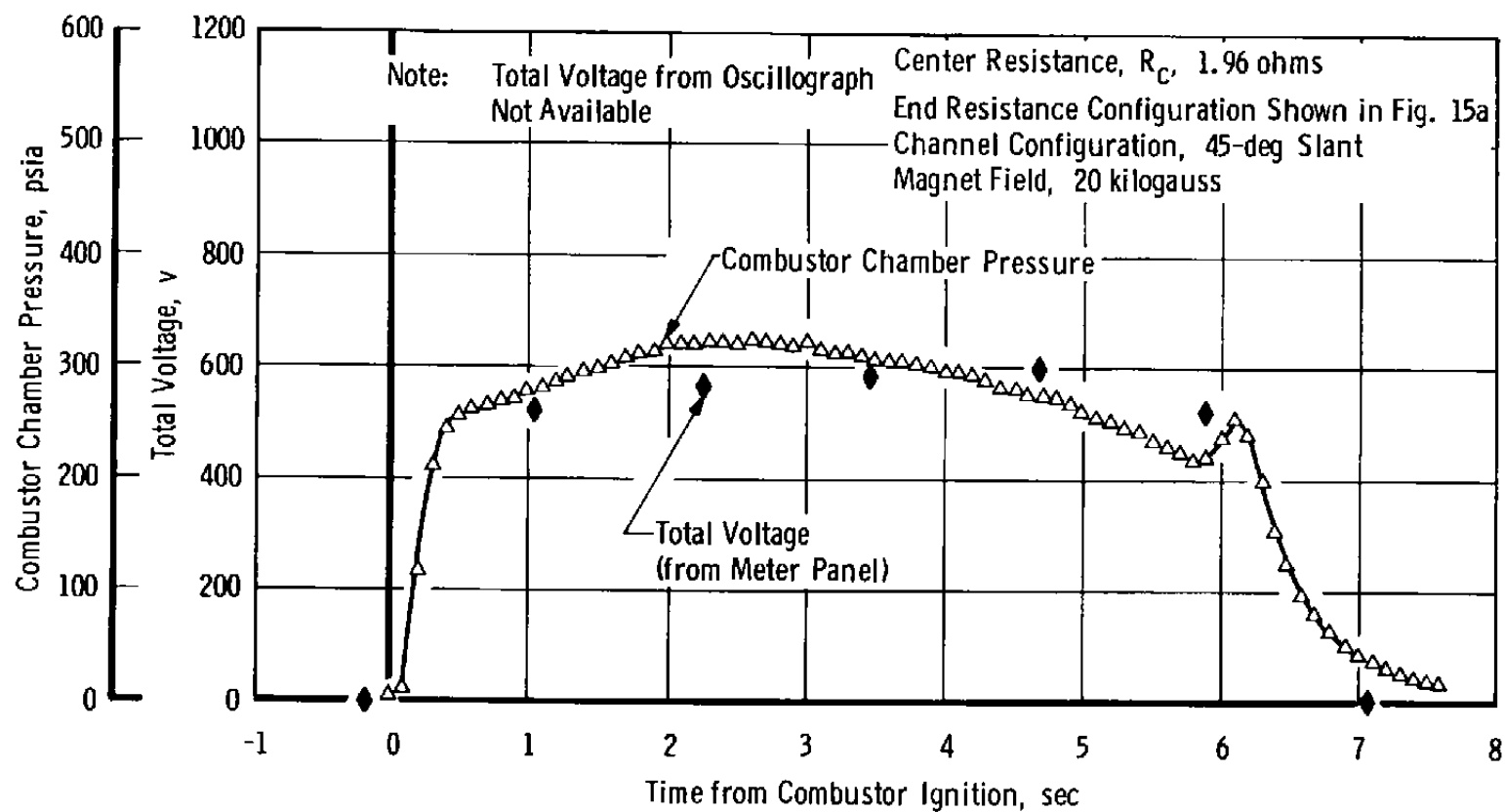
d. Firing No. 74

Fig. 21 Continued



e. Firing No. 75

Fig. 21 Continued



f. Firing No. 76

Fig. 21 Continued

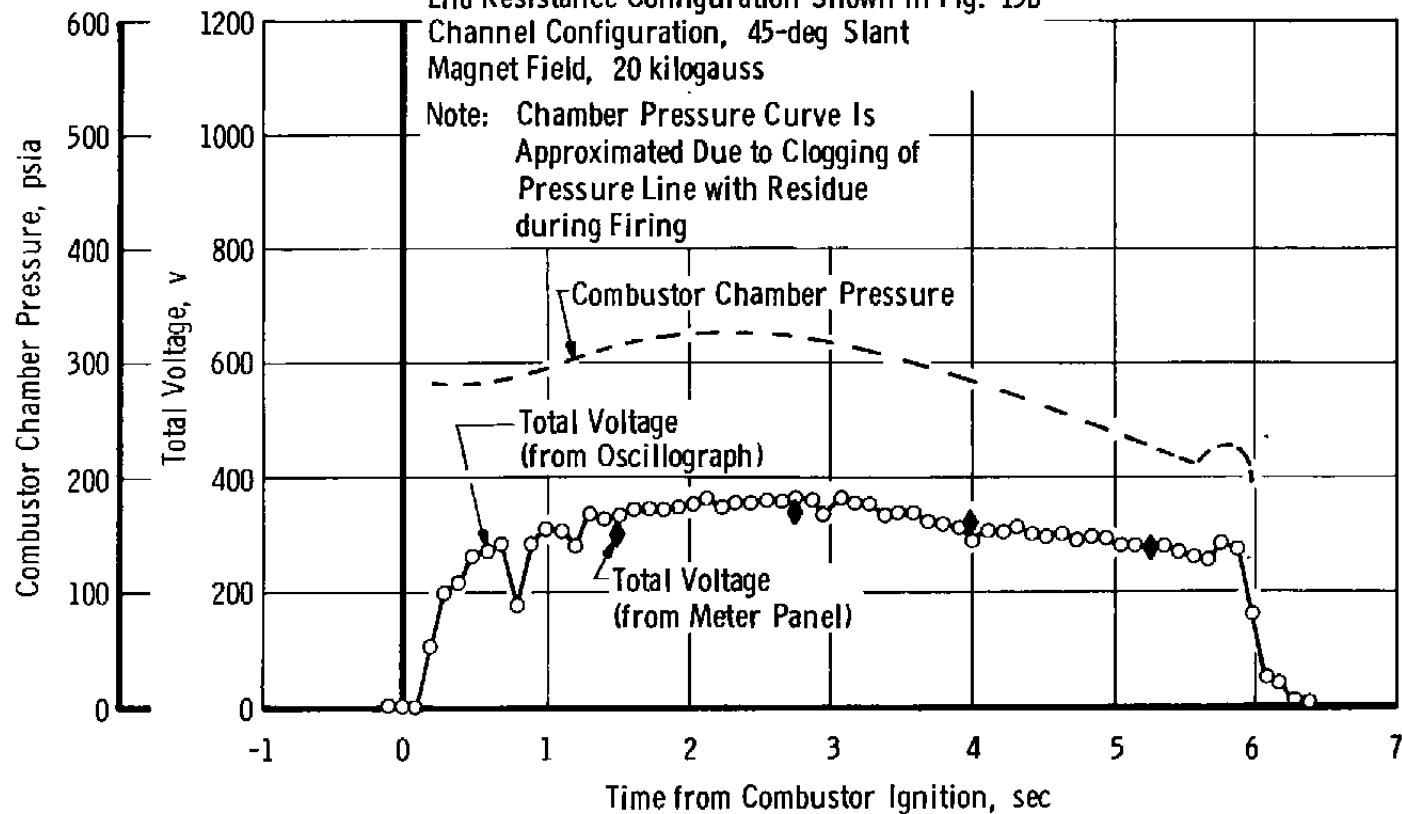
Center Resistance, R_C , 0.976 ohms

End Resistance Configuration Shown in Fig. 15b

Channel Configuration, 45-deg Slant

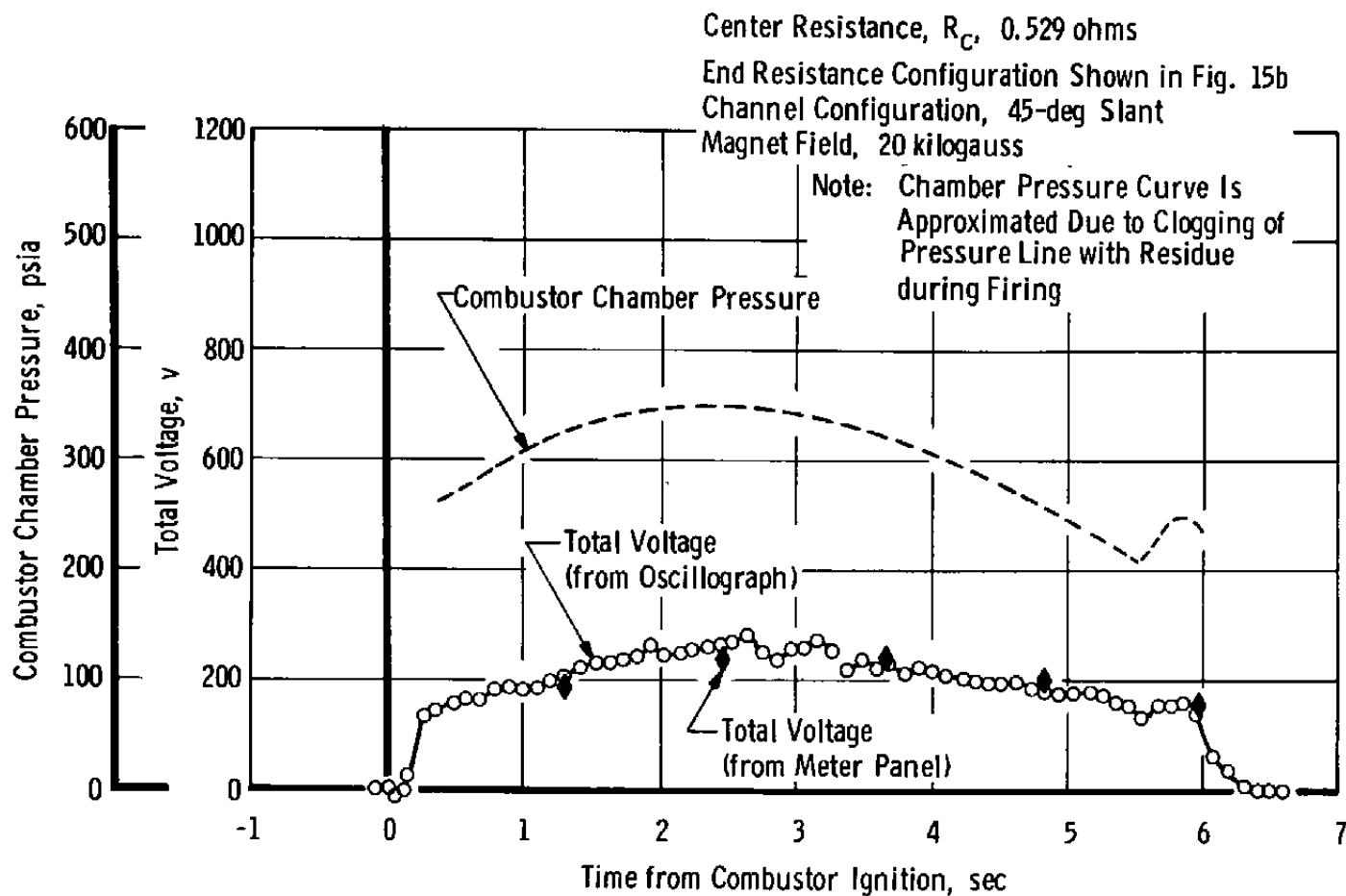
Magnet Field, 20 kilogauss

Note: Chamber Pressure Curve Is
Approximated Due to Clogging of
Pressure Line with Residue
during Firing



g. Firing No. 77

Fig. 21 Continued



h. Firing No. 79

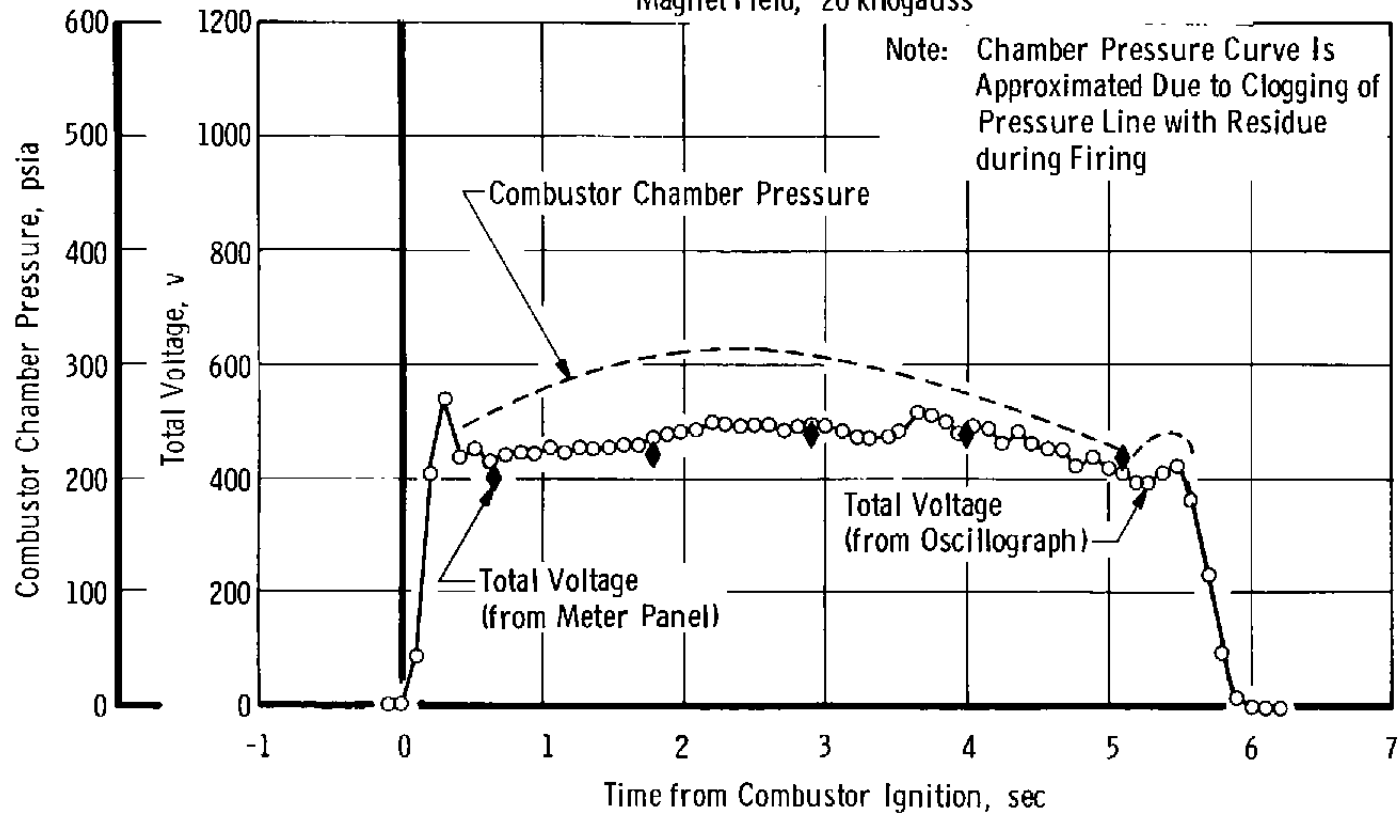
Fig. 21 Continued

Center Resistance, R_C , 1.96 ohms

End Resistance Configuration Shown in Fig. 15b

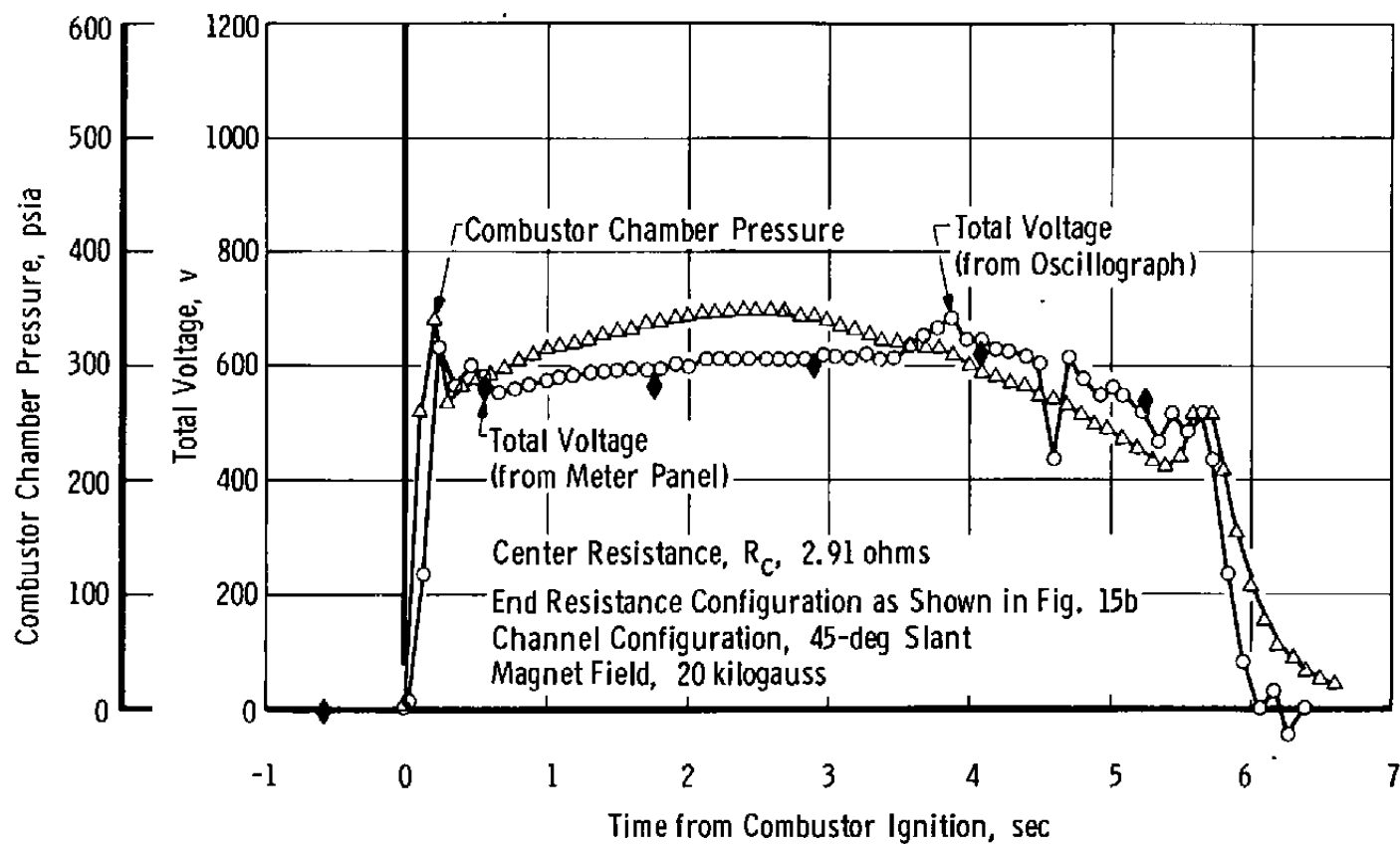
Channel Configuration, 45-deg Slant

Magnet Field, 20 kilogauss

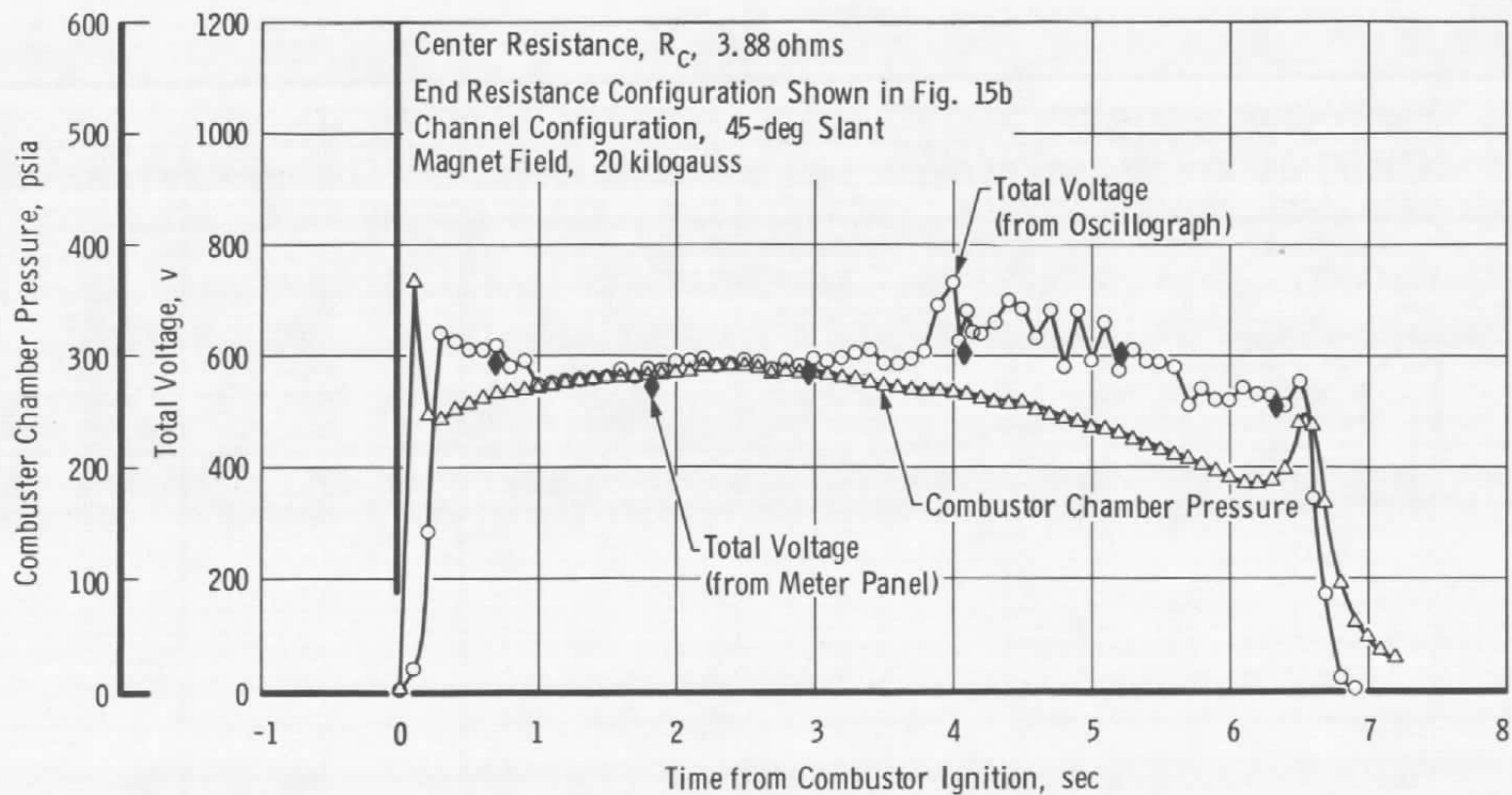


i. Firing No. 80

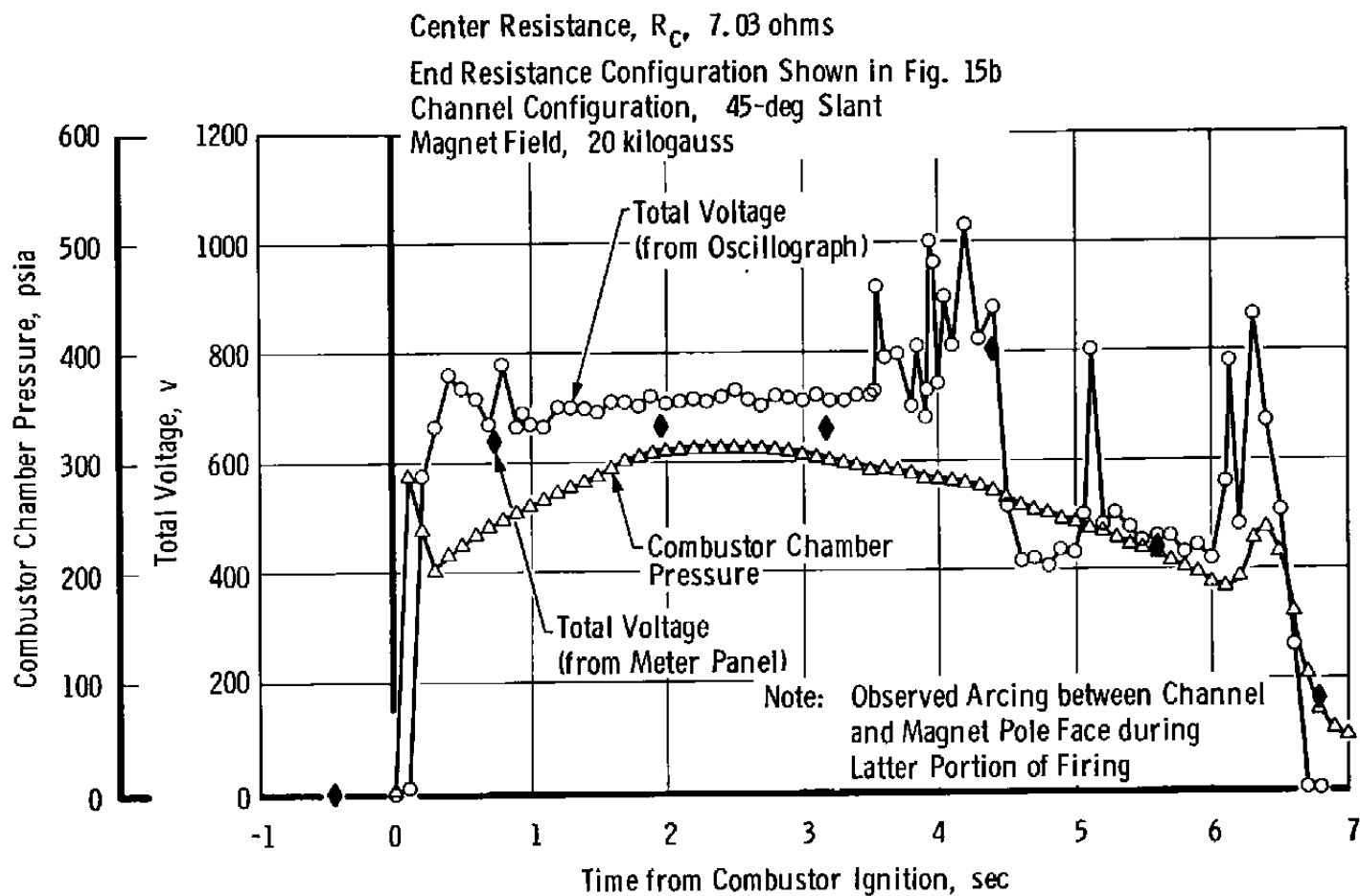
Fig. 21 Continued



j. Firing No. 81
 Fig. 21 Continued

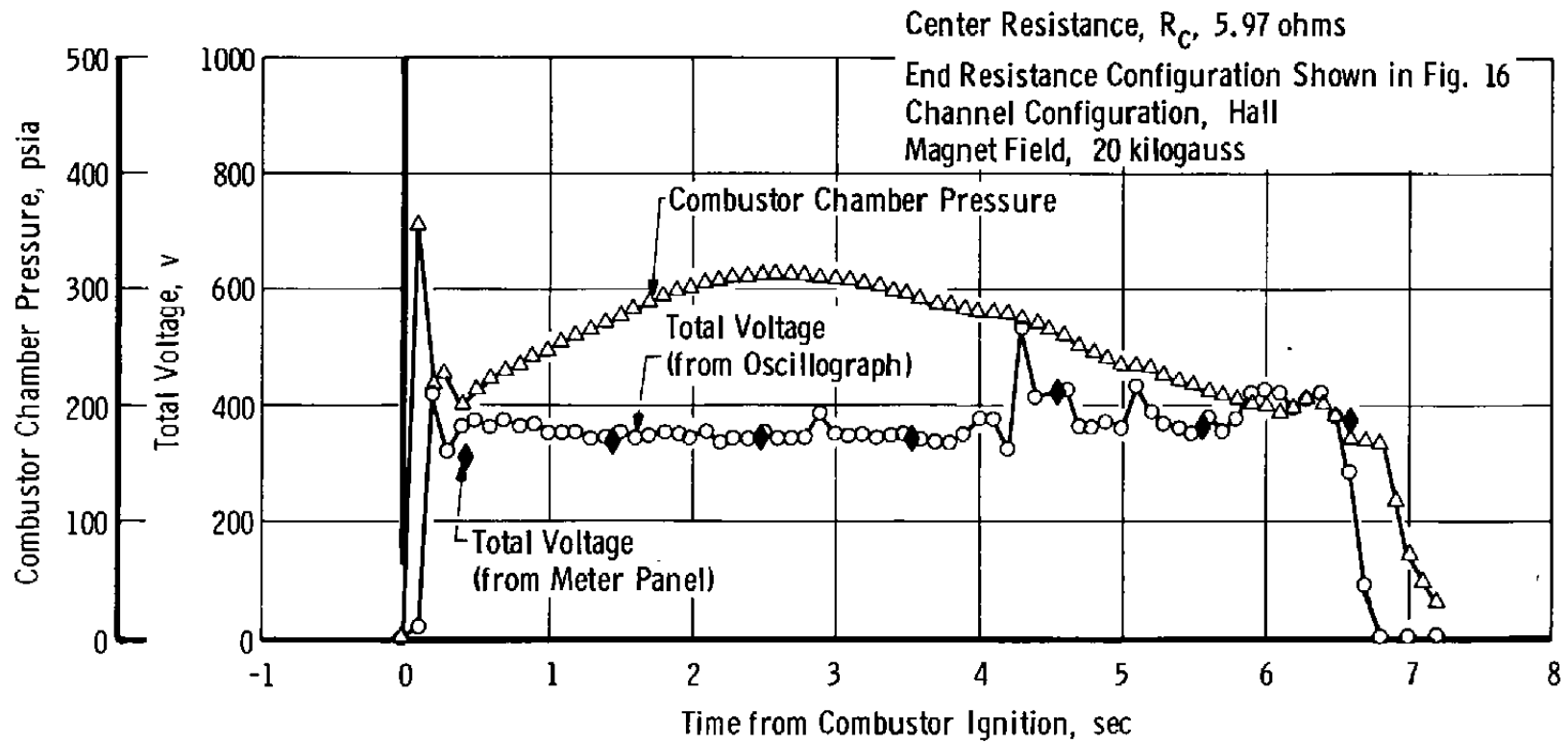


k. Firing No. 82
 Fig. 21 Continued



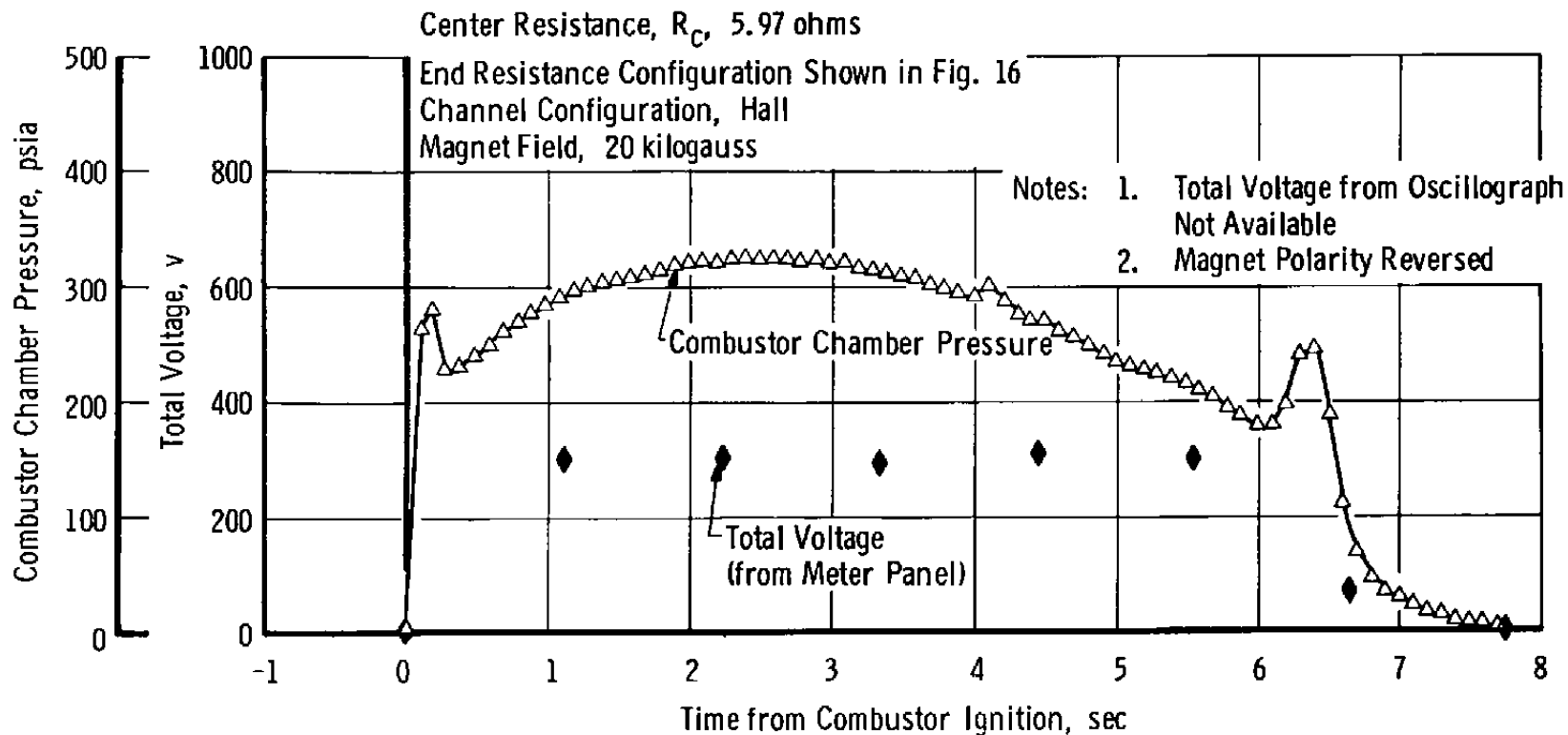
I. Firing No. 83

Fig. 21 Concluded

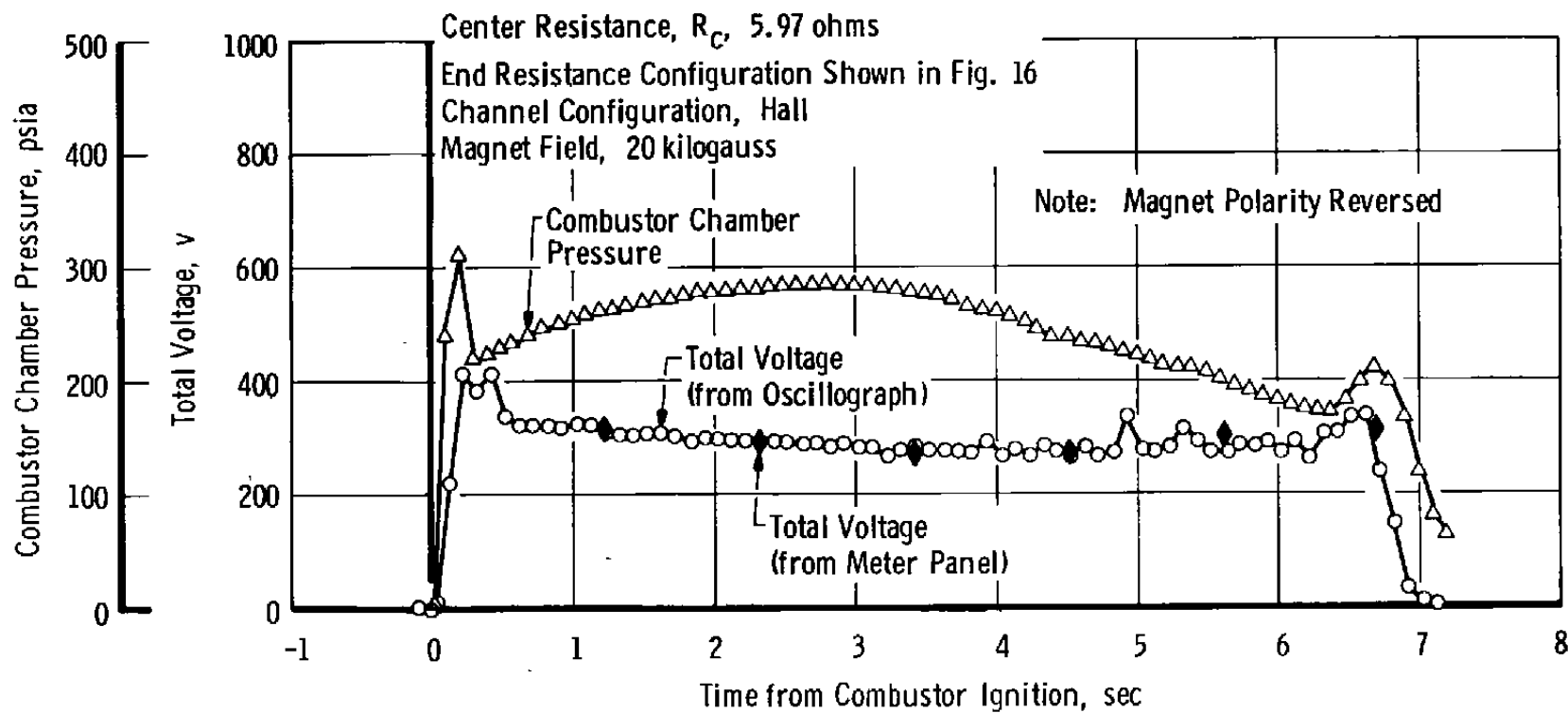


a. Firing No. 84

Fig. 22 Variation in Total Channel Voltage and Combustor Chamber Pressure during Hall Channel Power Generator Firings



b. Firing No. 85
 Fig. 22 Continued



c. Firing No. 86

Fig. 22 Concluded

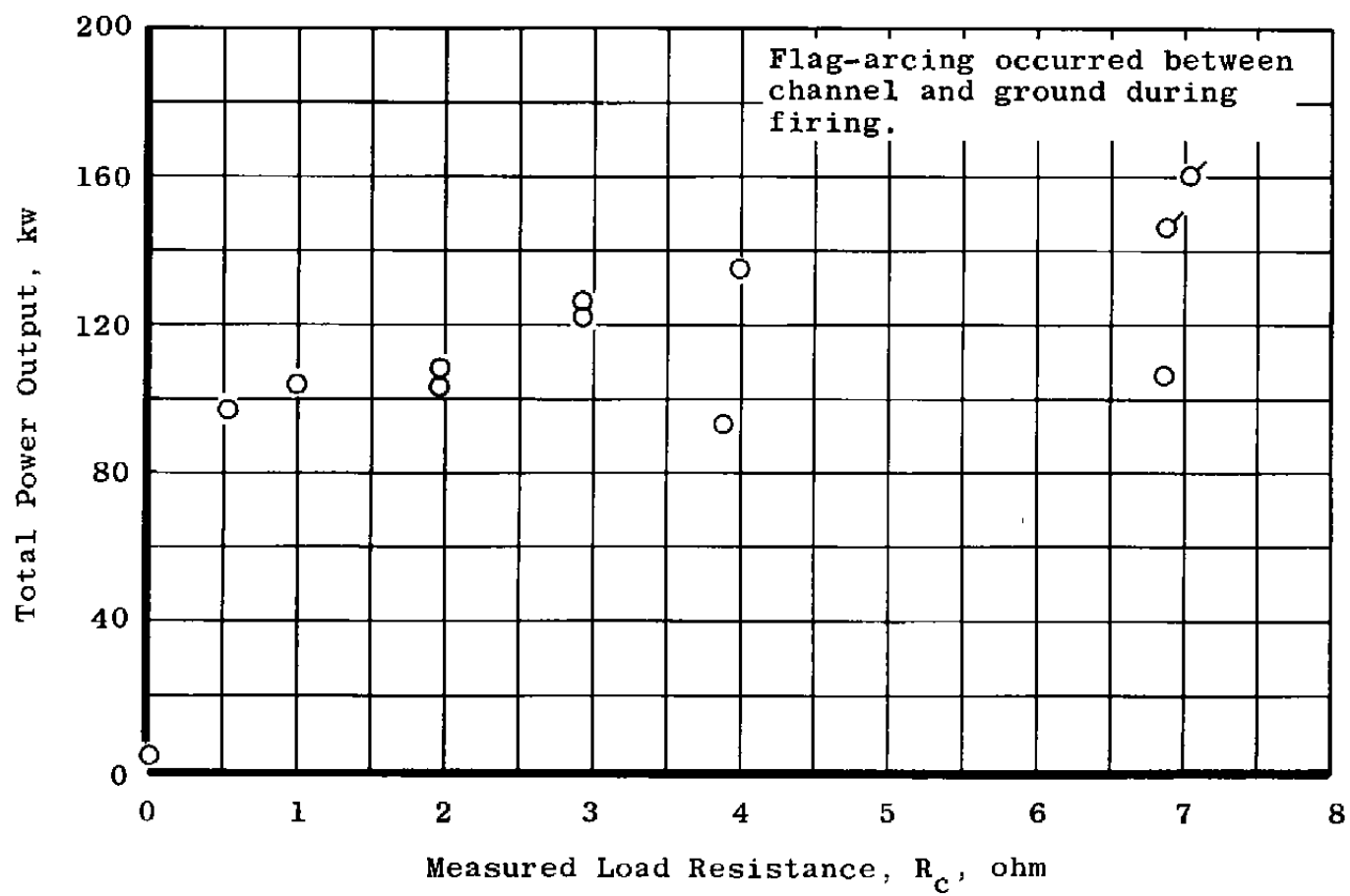


Fig. 23 Total Generated Power (45-deg-Slant Channel) as a Function of Center Resistance Load

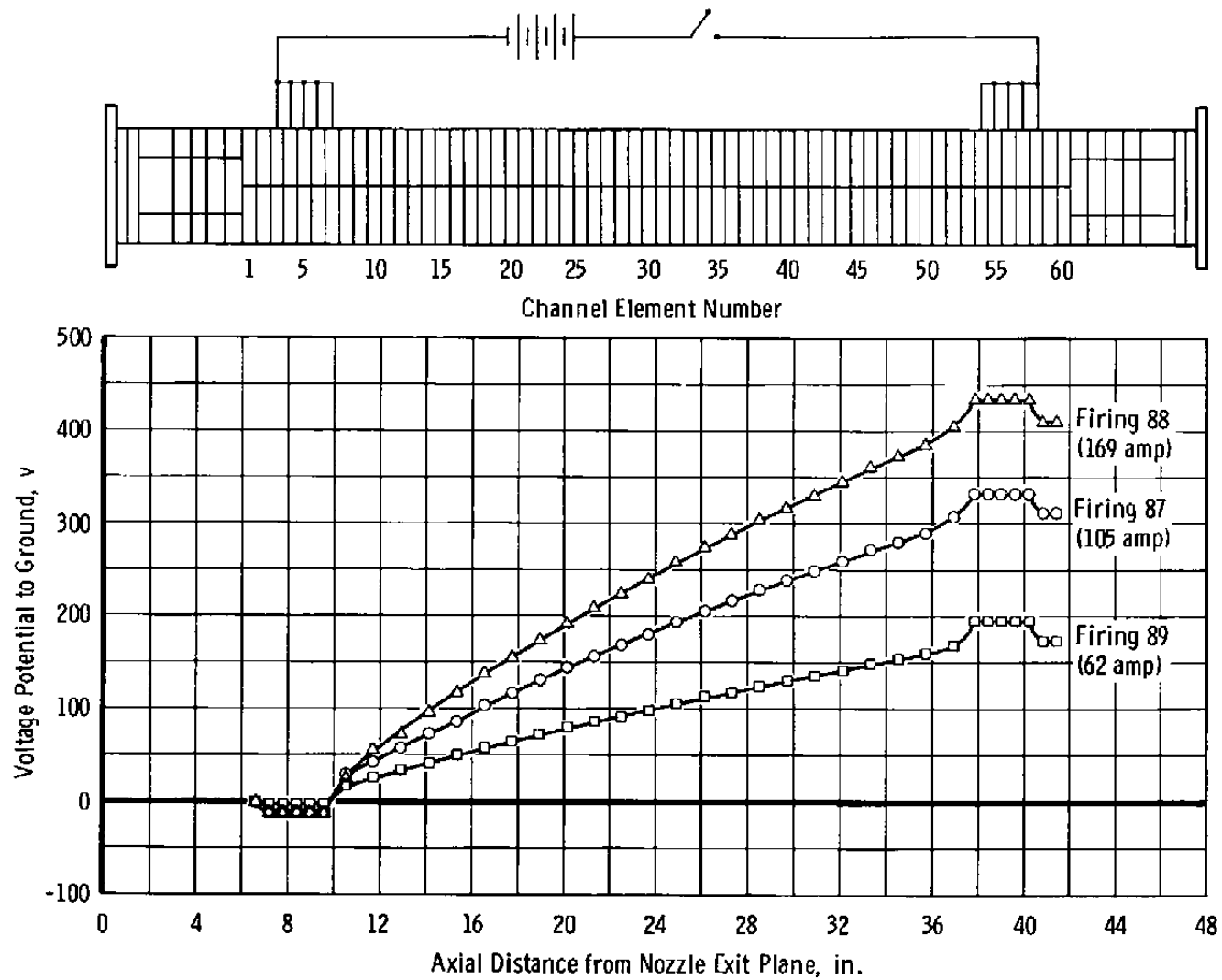


Fig. 24 Axial Voltage Distribution for Hall Channel Conductivity Measurement Firings

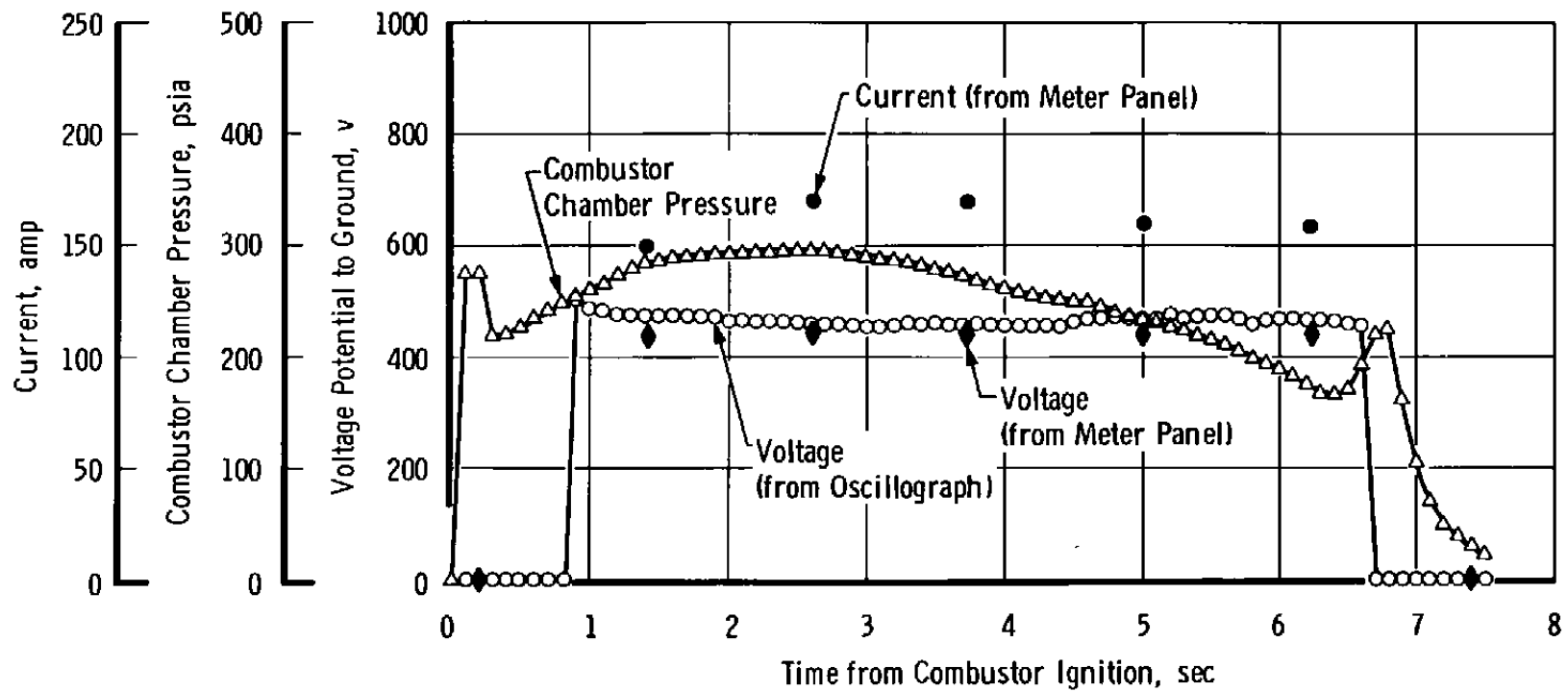


Fig. 25 Applied Voltage, Current Conducted through Plasma and Combustor Chamber Pressure during a Typical Conductivity Measurement Firing

TABLE I
INSTRUMENTATION

Parameter	Estimated Measurement Uncertainty (2 Sigma)			Type Measuring Device	Recording Device		Method of System Calibration
	Steady State		Range of Measurement		Type	Tape Channel Numbers	
	Percent of Reading	Units of Measurement					
Chamber Pressure, psia	±0.56	---	200 to 350 psia	Bonded Strain-Gage Pressure Transducers ↓	Voltage-to-Frequency Converter Onto Magnetic Tape	3, 6	Resistance Shunt ↓
Nozzle Exit Static Pressure, psia	±1.0	---	2 to 4 psia		Sequential Sampling Millivolt-to-Digital Converter and Magnetic Tape Storage Data Acquisition System ↓	---	
Spray Chamber Pressure, psia	±1.0	---	2 to 4 psia			---	
Channel Voltage	±1.0	---	-20 to 100 v	Voltmeter ↓	70-mm Camera ↓	---	Voltage Insertion ↓
	±1.0	---	0 to 1000 v			---	
Magnet Voltage	±1.0	---	0 to 120 v	Ammeter ↓		---	Current Insertion ↓
Channel Current	±1.0	---	-20 to 100 amp			---	
Magnet Current	±1.0	---	0 to 1200 amp			---	
Time Interval, msec	---	±5 msec	---	Synchronous Timing Generator	Photographically Recording Galvanometer Oscillograph	---	Compared to Frequency Standard

TABLE II
PERFORMANCE SUMMARY
a. Combustor

Run Number	Solid Fuel Grain Weight, lb _m	Nozzle Throat Area, in. ²		Nozzle Exit Area, in. ²		Action Time, t _a , sec	Augmented Combustor Chamber Pressure during t _a , psia	Maximum Combustor Chamber Pressure after Ignition Spike, psia
		Pre-Fire	Post-Fire	Pre-Fire	Post-Fire			
71	7.74	0.499	0.662	8.10	8.11	*	*	371
72	7.48	0.500	0.746	8.11	8.12	6.60	261	324
73	7.60	0.505	0.695	8.08	8.07	6.40	272	322
74	7.93	0.499	0.650	8.11	8.09	6.05	299	360
75	7.54	0.498	0.667	8.14	8.14	6.80	260	326
76	7.50	0.510	0.670	8.10	8.10	7.05	254	322
77	7.47	0.500	0.681	7.92	7.92	*	*	326
78	7.57	0.501	0.698	8.10	8.12	*	*	312
79	7.52	0.498	0.661	8.15	8.16	*	*	350
80	7.54	0.500	0.672	7.93	7.82	*	*	312
81	7.66	0.500	0.659	8.16	8.15	6.40	282	350
82	7.56	0.497	0.710	8.13	8.12	7.20	242	288
83	7.56	0.499	0.683	7.94	7.91	7.10	249	312
84	7.51	0.498	0.728	8.15	8.17	7.10	246	313
85	7.58	0.501	0.681	8.15	8.08	6.90	261	324
86	7.48	0.497	0.676	7.95	7.91	7.42	230	284
87	7.55	0.500	0.671	8.17	8.07	7.20	248	310
88	7.44	0.501	0.690	8.15	8.16	7.35	238	295
89	7.63	0.498	0.710	7.94	7.95	7.00	254	323

*Data invalid due to clogging of chamber pressure line with residue during firing

b. Generator Electrical
Table II Concluded

Run Number	Magnet		Load Bank Center Resistance				Total Generated Power, kw	Remarks
	Field Strength, Kilogauss	Polarity	Resistance Value, ohm	Voltage, v	Current, amp	Power, kw		
(5) 71	20 ↓	(1) Normal	6.87	(4) 936	---	128	146	45-deg-Slant Channel Power Generation ↓
72			∞	1000	0	0	0	
73			6.86	800	116	92.8	106	
74			3.99	720	169	122	135	
75			2.92	580	189	110	122	
76			1.96	440	216	95.0	103	
77			0.976	340	300	102	104	
78			0	0	450	0	3.00	
79			0.529	240	390	93.6	97.2	
80			1.96	460	229	105	108	
81			2.91	600	206	124	126	
(5) 82			3.88	600	150	90.0	92.5	
(5) 83			7.03	780	202	158	160	
84	↓	Reversed	5.97	400	65	26.0	27.2	Hall Channel Power Generation ↓
85			↓	300	51	15.3	16.4	
86			↓	310	51	15.8	16.4	
87	0	---	---	(2) 360	(3) 105	---	---	Hall Channel Conductivity Measurements
88	0	---	---	(2) 440	(3) 169	---	---	
89	0	---	---	(2) 200	(3) 62	---	---	

- Notes:
- (1) Magnet North pole located on channel right looking downstream
 - (2) dc voltage applied with external power supply across channel during firing
 - (3) Current conducted through plasma as result of externally applied voltage
 - (4) Calculated from oscillograph measurement of total channel voltage
 - (5) Arcing occurred between channel and ground during firing

TABLE III
SUMMARY OF MEASURED LOAD BANK RESISTANCES

Run Number	Measured Resistances, ohm																			
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R _{center}	R32	R33	R34	R35	R36	R37	R38	R39	R40	R41
71	0	0	0.211	0.205	0.236	0.281	0.303	0.340	---	5.870	---	---	0.300	0.246	0.227	0.199	0.199	0.169	0	0
72	0	0	---	0.205	0.236	0.281	0.303	0.340	---	---	---	---	---	---	---	---	---	---	---	---
73	0	0	0.204	0.204	0.231	0.256	0.300	0.336	---	5.860	---	---	0.335	0.246	0.225	0.201	0.201	0.175	0	0
74	↓	↓	↓	↓	↓	↓	↓	↓	---	3.990	---	---	↓	↓	↓	↓	↓	↓	↓	↓
75	↓	↓	↓	↓	↓	↓	↓	↓	---	2.920	---	---	↓	↓	↓	↓	↓	↓	↓	↓
76	0.167	0.111	0.066	0	0	0	0	0.291	---	1.960	---	---	0.273	↓	↓	↓	↓	↓	↓	↓
77	0.258	0.207	0.162	↓	↓	↓	↓	0.058	0.107	0.976	---	0.097	0.056	0	0	0	0	0.053	0.099	0.158
78	↓	↓	↓	↓	↓	↓	↓	↓	↓	0	---	↓	↓	↓	↓	↓	↓	0.157	0.194	0.255
79	↓	↓	↓	↓	↓	↓	↓	↓	↓	0.529	---	↓	↓	↓	↓	↓	↓	↓	↓	↓
80	↓	↓	↓	↓	↓	↓	↓	↓	↓	1.960	---	↓	↓	↓	↓	↓	↓	↓	↓	↓
81	↓	↓	↓	↓	↓	↓	↓	↓	↓	2.910	---	↓	↓	↓	↓	↓	↓	↓	↓	↓
82	↓	↓	↓	↓	↓	↓	↓	↓	↓	3.880	---	↓	↓	↓	↓	↓	↓	↓	↓	↓
83	↓	↓	↓	↓	↓	↓	↓	↓	↓	7.030	---	↓	↓	↓	↓	↓	↓	↓	↓	↓
84	0.104	0.057	0	0.061	0.102	---	---	---	---	5.970	0.098	0.056	0	0.054	0.098	---	---	---	---	---
85	↓	↓	↓	↓	↓	---	---	---	---	↓	↓	↓	↓	↓	↓	---	---	---	---	---
86	↓	↓	↓	↓	↓	---	---	---	---	↓	↓	↓	↓	↓	↓	---	---	---	---	---

TABLE IV
45-DEG-SLANT CHANNEL POWER GENERATION ELECTRICAL MEASUREMENTS
a. Current, Channel-to-Load Bank

Run Number	Time from Combustor Ignition, sec	Current, amp																		
		Element AB	Element BB	Element CB	Element DB	Element EB	Element FB	Element GB	Element HB	Element I	Element I-52	Element 52	Element AT	Element BT	Element CT	Element DT	Element ET	Element FT	Element GT	Element HT
71		Summary Data Only Available																		
72	4 53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
73	4 70	-32	-16	8	-8	11	-15	Void	-21	-24	116	36	22	7	0	-5	5	3	14	29
74	3 39	-42	-17	-7	-11	14	-18	-6	17	-98	169	76	30	20	1	10	10	6	14	26
75	4 02	-43	-14	-6	-9	10	-18	6	1	<-100	189	91	30	18	1	-8	11	-2	15	32
76	3 48	-17	-6	-3	-6	6	-10	-10	-25	<-100	216	<100	34	20	4	-4	8	6	14	24
77	2 76	-54	-43	-42	-44	-41	-37	-39	-26	4	300	14	19	18	18	31	32	42	52	84
78	2 32	70	-50	-52	-74	-52	-50	51	-32	-24	450	39	37	36	43	40	68	51	66	82
79	2 50	-42	-40	-29	+66	-57	-43	-59	-40	-25	390	22	24	28	31	42	65	48	60	74
80	4 10	-52	-42	-28	-34	-20	-20	-23	-11	-1	229	-10	14	11	16	31	40	40	45	54
81	4 10	-48	-40	-25	-32	-22	-19	-20	-10	11	206	-10	11	10	14	30	45	39	44	56
82	5 21	49	-39	25	-29	-18	-15	-14	-5	>20	150	Void	4	10	8	24	36	31	39	58
83	4 39	-36	-30	0	-39	-28	-15	14	-2	<20	202	Void	4	6	4	24	38	30	40	49

Note The electrical data presented in Tables IV and V were obtained from meter panel photograph which indicated the highest value of total channel voltage during each firing

Table IV Continued

Run Number	Time from Combusitor Ignition, sec	Current, amp																									
		Element 1	Element 3	Element 5	Element 7	Element 9	Element 11	Element 13	Element 15	Element 17	Element 19	Element 21	Element 23	Element 25	Element 27	Element 29	Element 31	Element 33	Element 35	Element 37	Element 39	Element 41	Element 43	Element 45	Element 47	Element 49	Element 52
71		Summary Data Only Available																									
72	4 53	52	46	23	28	19	42	16	31	30	32	30	32	36	40	14	25	30	32	28	32	37	30	32	34	33	40
73	4 70	32	19	19	20	22	21	25	28	26	24	24	27	38	39	14	28	35	34	33	34	38	32	37	36	30	10
74	3 39	>100	27	24	26	29	28	33	40	36	38	36	40	34	38	20	39	40	44	39	43	40	38	38	36	26	3
75	4 92	>100	22	20	26	26	27	35	36	36	35	40	38	37	40	20	34	37	42	37	39	37	38	37	33	30	0
76	3 48	>100	29	26	48	43	38	48	45	46	52	56	42	44	44	27	46	48	44	39	43	40	39	40	34	30	0
77	2 76	28	43	40	50	52	52	54	47	57	51	56	52	47	50	46	46	47	40	38	39	34	34	30	30	26	7
78	2 32	40	28	30	42	40	38	42	38	37	34	46	44	33	39	33	34	32	30	30	31	30	26	25	24	20	0
79	2 50	45	40	43	53	55	60	58	52	57	59	64	52	52	53	51	46	46	43	43	43	42	35	35	31	27	4
80	4 10	14	20	22	23	27	28	36	34	38	37	42	40	40	42	22	38	42	40	38	41	38	36	36	34	33	54
81	4 16	10	22	20	22	22	23	29	31	31	31	30	35	40	42	19	34	40	40	43	43	39	41	37	37	32	80
82	5 21	5	20	20	20	26	26	29	30	32	33	34	31	33	38	19	32	30	30	33	32	31	30	28	30	25	69
83	4 39	2	26	28	31	32	32	40	40	47	40	44	40	41	37	36	40	36	37	34	34	34	34	32	33	22	>100

c. Channel Voltage Distribution

Table IV Concluded

Run Number	Time from Combustion Ignition, sec	Voltage Difference, v																	
		Element A ₁ - Element B ₃	Element B ₃ - Element C ₅	Element C ₅ - Element D ₇	Element D ₇ - Element E ₉	Element F ₉ - Element F ₃	Element F ₃ - Element G ₅	Element G ₅ - Element H ₇	Element H ₇ - Element I ₉	Element I ₉ - Element 52	Element 52 - Element A ₁	Element A ₁ - Element B ₃	Element B ₃ - Element C ₅	Element C ₅ - Element D ₇	Element D ₇ - Element E ₉	Element E ₉ - Element F ₃	Element F ₃ - Element G ₅	Element G ₅ - Element H ₇	Element H ₇ - Element I ₉
71		Summary Data Only Available																	
72	4 53	20	3		30	28	22	8	24	1000	26	13	8		10	13		12	14
73	4 70	0	0	10	12	12	3	35	30	800	24	14	2	10	10	8	0	0	0
74	3 39	0	0	13	16	14	20	30	22	720	20	Void	10	10	11	10	0	0	0
75	4 02	0	0	12	14	16	22	22	22	580	28	12	10	10	10	8	0	0	0
76	2 48	0	0	4	6	5	10	14	19	140	20	17	11	10	10	8	0	0	0
77	2 76	4	2	2	0	0	0	0	0	340	0	-1	0	0	0	2	2	8	8
78	2 32	6	4	8	0	0	0	0	0	0	-2	-1	0	0	0	8	4	8	8
79	2 50	4	3	4	0	0	0	0	0	240	0	-1	0	0	0	8	3	6	6
80	4 10	6	4	4	0	0	0	0	0	460	5	0	0	0	0	6	2	6	6
81	4 16	4	4	3	0	0	0	0	0	600	8	0	0	0	0	6	0	6	6
82	5 21	4	4	3	0	0	0	0	4	600	6	0	0	0	0	4	0	5	5
83	4 39	4	20	30	0	0	0	0	5	780	2	0	0	0	0	4	1	4	4

TABLE V
HALL CHANNEL POWER GENERATION ELECTRICAL MEASUREMENTS
 a. Current, Channel-to-Load Bank

Run Number	Current, amp											
	Time from Combustor Ignition, sec	Element 1	Element 2	Element 3	Element 4	Element 5	Element 5 - 56	Element 56	Element 57	Element 58	Element 59	Element 60
84	4.55	-60	-25	0	-2	Void	65	<-20	-12	11	28	74
85	4.43	-56	-18	0	4	20	51	-53	-16	5	87	24
86	6.79	-38	-17	0	3	3	51	-50	-13	6	82	21

Note: The electrical data presented in Tables IV and V were obtained from meter panel photograph which indicated the highest value of total channel voltage during each firing.

b. Current, Channel Element Top-to-Element Bottom

Table V Continued

Run Number	Time from Combuator Ignition, sec	Current, amp																																				
		Element 1	Element 2	Element 3	Element 4	Element 5	Element 6	Element 7	Element 9	Element 11	Element 13	Element 15	Element 17	Element 19	Element 21	Element 23	Element 25	Element 27	Element 29	Element 31	Element 33	Element 35	Element 37	Element 39	Element 41	Element 43	Element 45	Element 47	Element 49	Element 51	Element 53	Element 54	Element 55	Element 56	Element 57	Element 58	Element 59	Element 60
84	4.55	57	27	16	20	10	22	20	28	28	24	31	28	36	31	33	34	Void	40	Void	Void	Void	41	37	36	40	38	36	39	43	18	32	31	57	34	14	8	Void
85	4.43	-20	-16	-22	-26	-42	-36	-37	-40	-31	-40	-38	-47	-39	-35	40	-40	-35	-37	38	-37	-36	-42	-38	-38	-39	-36	-39	-42	-52	-20	-43	-43	-22	-23	-28	-100	-30
86	6.79	-12	-12	-14	-16	-20	-19	-20	-22	-18	-18	-20	-20	-19	-23	-24	-26	-26	-28	-24	-28	-29	-30	-30	-28	-28	-24	-31	-28	-35	-22	-34	-35	-18	-18	-20	-98	-23

c. Channel Voltage Distribution

Table V Concluded

Run Number	Time from Combustor Ignition, sec	Voltage Difference, v								
		Element 1 - Element 2	Element 2 - Element 3	Element 3 - Element 4	Element 4 - Element 5	Element 5 - Element 56	Element 56 - Element 57	Element 57 - Element 58	Element 58 - Element 59	Element 59 - Element 60
84	4.55	4	-2	2	2	400	4	0	Void	6
85	4.43	4	-2	2	0	300	4	0	4	-3
86	6.79	4	0	1	0	310	4	0	4	-3

TABLE VI
ELECTRICAL DATA SUMMARY OF HALL CHANNEL CONDUCTIVITY MEASUREMENTS
a. Voltage Distribution

[illegible]

b. Current from Power Supply
Table VI Concluded

Run Number	Time from Motor Ignition, sec	Current, amp										
		Element 3	Element 4	Element 5	Element 6	Element 7	Element 54	Element 55	Element 56	Element 57	Element 58	Current Input to Channel, amp
87	4 34	14	18	12	17	46	-73	-8	-13	-8	-2	105
88	3 73	16	21	17	22	92	<-100	-13	-18	-11	-4	169
89	3 28	8	11	11	13	22	-41	-3	-7	-10	-1	52

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13. ABSTRACT A test program was conducted for the University of Tennessee Space Institute on a vertically segmented wall (Hall) and a diagonally seg- mented wall (45-deg-slant) magnetohydrodynamic generator. The internal width of the 48-in.-long generator channel was 2 in.; the height diverged from 4 in. at the inlet to 6 in. at the exit. The plasma was provided by a solid-fueled combustor with a nozzle designed for an exhaust gas exit Mach number of 3.75. Thirteen firings were made with the 45-deg-slant channel for power generation. Six firings were made with the Hall channel; three of these were for power generation, and three were made for exhaust gas conductivity measurement. Operating conditions for the power generation firings were: nominal combustor chamber pressure, 325 psia; magnetic field, 20,000 gauss; and load bank resistance from 0 to ∞ ohms. For the exhaust gas conductivity measurements, voltage was supplied to the channel at levels of 360, 440, and 200 v dc. Tabulations of combustor performance and of the electrical data from the two generator configurations are presented. This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Air Force Aero-Propulsion Laboratory (APIE-2), Wright-Patterson Air Force Base, Ohio 45433.			

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